A MATHEMATICAL MODEL OF THE R-H VACUUM DEGASSING SYSTEM

by

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ABSTRACT

A mathematical model has been developed to describe the fluid flow field, the turbulence parameters and the rate at which oxide inclusion particles are removed by coalescence in an R-H Vacuum Degassing Unit.

The problem is stated through the turbulent Navier-Stokes equations, the k-ε model for the turbulent viscosity and a coalescence mode.

The governing equations are solved numerically and a population balance model is being employed to represent the size distribution of the oxide particales.

The computed results indicate that the R-H unit is an excellent mixer and that the principal mechanism of the coalescence process is the adequate supply of the material contained in the ladle to the locations in the vicinity of the "down-leg" where the rate of turbulent energy dissipation is the greatest.

The computed results also show that the spatial distribution of particles of different size is quite uniform. Finally, the overall deoxidation rates predicted by the model appear to be in agreement with rates observed in industrial pratice.

Thesis supervisor: Dr. Julian Szekely

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CHAPTER 1

Introduction

In recent years there has been a growing interest in "clean steel" production because the oxide particles which are formed during deoxidizing process adversely affect the mechanical properties of the products. The studies on rate phenonomena of deoxidation have been made by the many investigators. Theoretical considerations suggest that the factors influencing the growth and floatation of inclusions, i.e. deoxidation products, are complex, however the extent of inclusion growth by Brownian motion and Ostwald ripening is insignificant. On the basis of available experimental results, the rate of deoxidation is enhanced by the highly agitated melts in which the collision frequency is more rapid than in stagnant melts. The concept of the collision model in a turbulent field had been investigated by the researchers of meteorology or aerosol science. A simple application of this coagulation theories to the present problem seems to lead a reasonable agreement with experimental results.

The R-H vacuum degassing system has gained a widespread acceptance for decades due to its capacity of gaseous impurities removal and high mixing. At present the R-H treatment is employed not only to remove these impurities but also to gain the high mixing rate, i.e. to produce a strong turbulent field. The R-H unit makes it possible to achieve the rapid removal rate of oxide particles from the melt.

The purpose of this thesis is to make the attempt to simulate the deoxidation process in R-H unit by combining a turbulence theory and O_2 particle coagulation theory.

The work to be described in this thesis represents the attempts toward a predictive model for flow and deoxidation characteristics of R-H degassing process. The model for the oxidie particle coalescence is employed in order to simulate the deoxidation process.

This thesis, is divided into six chapters.

In chapter 2 a literature survey is presented, which reviews the particle movement in turbulent flow, the particel population balance, the particle deposition theory, and the particle coalescence theory. The available turbulence model are also surveyed.

Chapter 3 gives the formulation of the mathematical model. After describing the R-H degassing unit and discussing the assumption made, the general form of the governing differentical equations is given and the coefficients and the source term are represented.

In chapter 4 the numerical technique is outlined which was employed to solve the differential equations.

In Chapter 5 computed results on fluid field and particle distribution are discussed. The rate of deoxidation in R-H degasser is also treated here.

Finally, concluding remarks and some suggestions for future work are made in chapter 6.

Chapter 2 LITERATURE SURVEY

In this chapter, the R-H degassing system is first described briefly. Next, the deoxidation machanism is reviewed. In the later part of this chapter, the mathematical models for the coalescence frequency, the particle population balance, the turbulent flow and the particle deposition are described.

2.1 R-H Vacuum Degasser

The Ruhrstahl-Heraeus vacuum degassing process was originally developed in order to remove the gaseous impurities whose solubility in steel melts decrease under vacuum. This system has been useful for removing impurities like hydrogen and nitrogen which have an adverse effect on the mechanical properties of the final product. In addition the vacuum atmosphere accelerated the reaction between dissolved carbon and oxygen, so that some effects on decarburization may be expected. Another benefit of using the R-H system is that it allows a better yield of deoxidizers or other alloying additions because the tendency to oxidize is reduced under vacuum.

In the R-H degassing process, as shown in Fig. 2.1, two legs are immersed in a steel melt and an inert gas is injected into one leg (called the up-leg). The injected bubbles induced a buoyancy force which produces a recirculating flow through the vacuum vessel and ladle. This mixing effect is considerably larger than with argon stirring or other mixing arrangements [2-3]. Several reports were published to determine the recirculation rate in this system, mostly from laboratory scale models or industrial scale experiments[1,4]. An understanding of the recirculation rate is very important in order to obtain optimal gas flow rate and other operational parameters. Some extensive work has been done to define the state of mixing in R-H units and theoretical predictions regarding the time required for dispersion have been

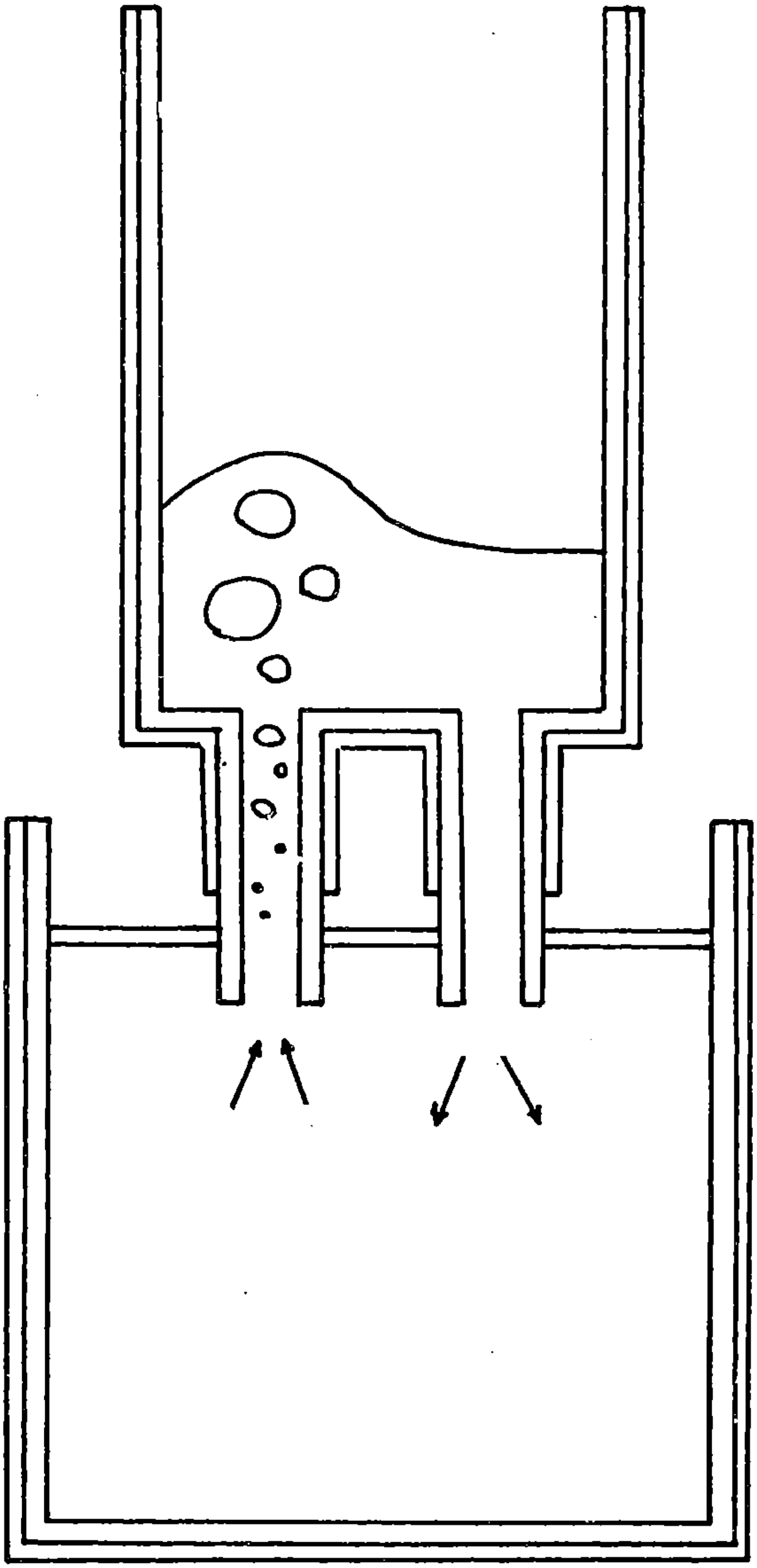


Fig. 2.1 Schematic diagram of the R-H degasser

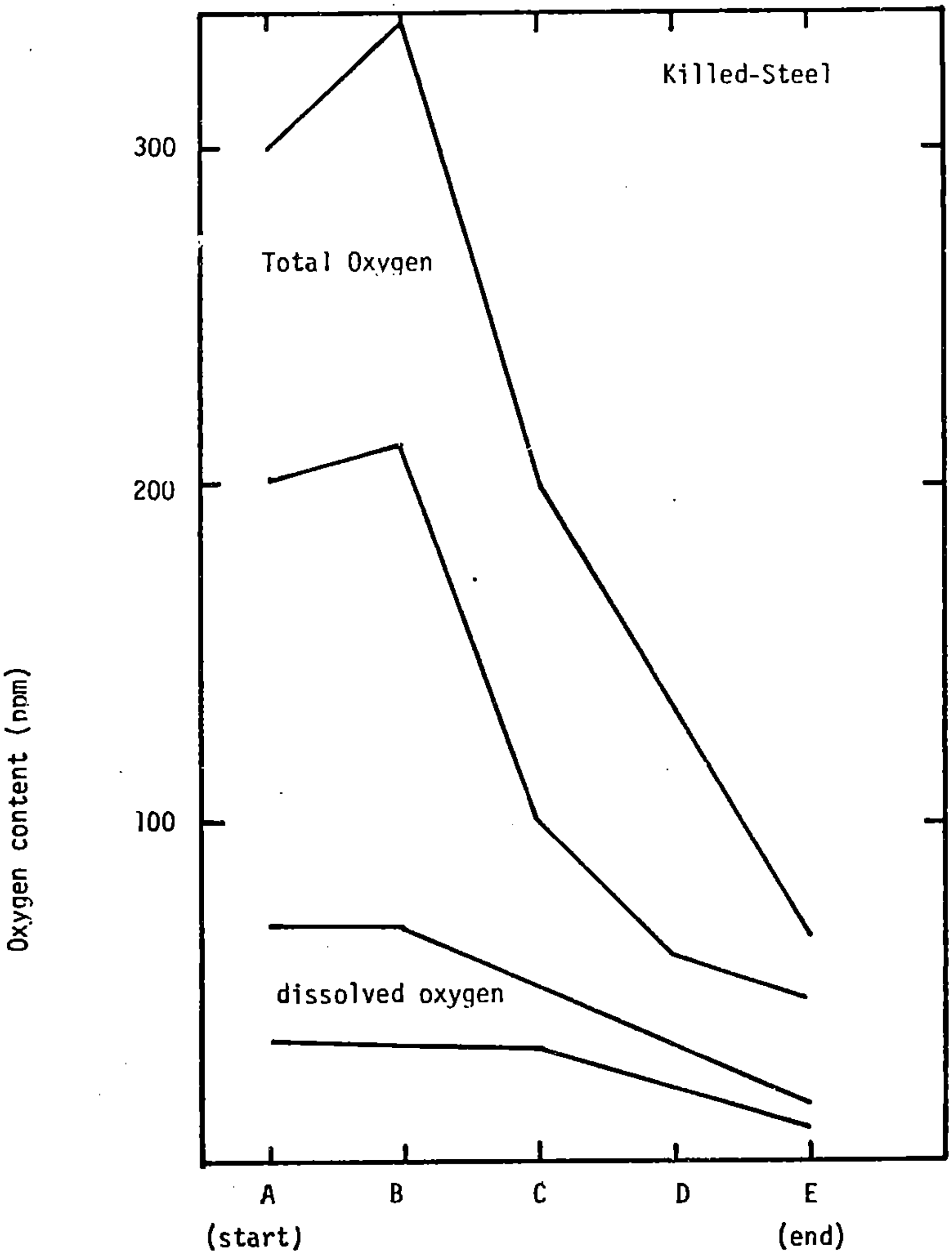


Fig. 2.2 Schematic representation of total oxygen and dissolved oxygen

made [1]. These predictions seem to be in good agreement with experimentally obtained time response curves.

This mixing capability gives another advantage to the R-H system in addition to the effective dispersion of additions: the coalescence and floatation of inclusions. The effect is not unique to this system, but common to the processes in which a steel melt is strongly agitated by forced convection (e.g. ASEA-SKF, [5] Argon stirred ladles, or TN-method). However, a few investigations have been done regarding the turbulent characteristics in R-H units and their effect on the removal of inclusions.

The decrease of inclusions is shown schematically in Fig. 2.2. Since various additions are made during treatment, it is difficult to deduce the effect of mixing on the rate of deoxidation. However, the total oxygen content increases slightly during the first stage and then decreases remarkably [54]. The value of the dissolved oxygen is constant at the initial step, but decreases gradually. The rate of reduction of total oxygen (most of which may be oxygen in the form of oxidides) is much faster than that of dissolved oxygen.

2.2 Deoxidation Mechanism

A large number of articles have been published dealing with deoxidation [13-18]. According to Turkdogan [14], the deoxidation reaction may be separated into three steps: formation of critical nuclei of the deoxidation product; progress of deoxidation resulting in growth of the reaction products; and floatation form the melt.

As for the nucleation, Turkdogan [15] suggested that the number of nuclei formed at the time of addition of the deoxidizer is about $10^8/cm^3$. However, the time for nucleation is far less than 1 sec. [13] (for SiO_2 $1x10^{-6}$sec).

Regarding the growth process, Turkdogan [14] suggested four major mechanisms: (a) Brownian motion, (b) Ostwald ripening, (c) diffusion, and (d) collision. Brownian motion is such a slow process that it would take 3 hours to reduct eht oxidized particle density to 10^7 particles/cm^3. Ostwald ripening is the process for the system of dispersed particles of varying size and the smaller ones dissolve and the larger ones grow. The driving force is the interfacial energy. This process is also very slow [14, 16, 19]. Turkdogan also discussed the subject of diffusional growth [15]. The rate of oxidized particle removal by collisions was measured by several investigators [19, 20, 21]. A theoretical explanation of this problem was proposed by Lindborg et al. [19] who used the equations derived by Gunn [25] and by Saffman and Turner [26].

2.3 General Mechanism of Particle Movement in Turbulent Flow

In a turbulent dispersion a knowledge of ralative motion of particles to surrounding fluid is of great importance for an understanding of the coagulation mechanism between particles, and the mass transfer from particles to fluid. The behavior of descrete particles in a turbulent fluid depends largely on the concentration of the particles and on their size relative to the scale of turbulence. The first extensive theoretical study was made by Tchen [6] on the motion of very small particles in a turblent fluid. In Tchen's theory the following assumptions are made

1) The turbulence of the fluid is homogeneous and steady.
2) The domain of turbulence is infinite in extent.
3) The particle is spherical and so small that its motion relative to the ambient fluid follows Stokes' law of resistance.
4) The particle is small compared with the smalles wavelength presented in turbulence, i.e. with the Kolmogorov micro-scale η.
5) During the motion of the particle the neighborhood is by the same fluid.
6) Any external force acting on the particle originates from a potential field, such as gravity.

Assumption (4) seems to be valid for the present problem since the dissipation rate of turbulence in a ladle, ε, is at most 100erg/g, thus the Kolmogorov micro scale length, η, is about 400μm. This length is much larger than the particle diameter being considered. Other assumptions may be valid for the present problem.

The basic equation extended by Tschen is as follows, [6-9];

$$\underset{(1)}{\frac{\pi}{6} d_p^3 \rho_p \frac{dv_p}{dt}} = \underset{(2)}{\frac{\pi}{8} d_p^2 \rho_f C_d |v_f - v_p| (v_f - v_p)} + \underset{(3)}{\frac{\pi}{6} d_p^3 \rho_f \frac{dv_f}{dt}} + \underset{(4)}{\frac{1}{2}\frac{\pi}{6} d^3 \rho_f \left(\frac{dv_f}{dt} - \frac{dv_p}{dt}\right)} + \underset{(5)}{\frac{3}{2} d_p^3 \sqrt{\pi \rho_f u} \int_{t_0}^{t} dt' \frac{\frac{dv_f}{dt'} - \frac{dv_p}{dt}}{\sqrt{t-t'}}} + \underset{(6)}{F_e} \qquad (2.2.1)$$

where V_p and V_f are the turbulent velocities of fluid and particle, d_p the diameter of particle, C_d the drag coefficient in turbulent flow, and ρ and ρ_p the densities of fluid and particles. Each term means the following:

(1) the force required to accelerate the particle,

(2) drag force,

(3) pressure gradient force,

(4) added mass correction,

(5) Basset term,

(6) external force due to potential field.

When the potential force term is neglected equ. (2.2.1) can be rewritten as follows.

$$\frac{dv_p}{dt} + a v_p = a v_f + b \frac{dv_f}{dt} + c \int_{t_0}^{t'} dt' \frac{dv_f/dt' - dv_p/dt'}{\sqrt{t - t'}} \qquad (2.2.2)$$

where

$$a = \frac{36\mu}{(2\rho_p + \rho_f)d^3} \qquad b = \frac{3\rho_f}{2\rho_p + \rho_f} \qquad c = \frac{18}{(2\rho_p + \rho_f)d}\sqrt{\frac{\rho_f \mu}{\pi}}$$

Interesting results will be obtained if we assume that both V_p and V_f may be represented by a fourier integral [6].

$$v_f = \int_0^\infty d\omega\,(\alpha \cos \omega t + \beta \sin \omega t) \qquad (2.2.3)$$

$$v_p = \int_0^\infty d\omega\,(\gamma \cos \omega t + \delta \sin \omega t) \qquad (2.2.4)$$

Then the ratio between Lagrangian energy-spectrum functions for fluid and particles may be expressed as follows [6]

$$\frac{E_{pL}}{E_{fL}} = [1 + f_1(\omega)]^2 + f_2^2(\omega) \qquad (2.2.5)$$

where
$$f_1(\omega) = \frac{\omega(\omega + c\sqrt{\pi\omega/2}(b-1)}{(a + c\sqrt{\pi\omega/2})^2 + (\omega + c\sqrt{\pi\omega/2})^2}$$

$$f_2(\omega) = \frac{\omega(a + c\sqrt{\pi\omega/2})(b-1)}{(a + c\sqrt{\pi\omega/2})^2 + (\omega + c\sqrt{\pi\omega/2})^2}$$

Assuming Pao's universal slope law (Fig. 2.3) for the spectrum distribution in the R-H units, we can obtain the energy spectrum distribution for the particle using equ. (2.2.5) (Fig. 2.4). For the present calculation a dissipation energy of ε = 500 (erg/cm^3) is used. There is only a slight difference between the energy spectrum of fluid and particles. On the other hand, Peskin [11-12] obtained the following relation between diffusivities of fluids and particles;

$$\frac{D_p}{D} = 1 - \frac{\lambda^2}{\lambda_E^2}\left(\frac{3K^2}{K+2}\right) + O\left(\frac{1}{\lambda_E^4}\right) \tag{2.2.6}$$

where K $\doteq (\sqrt{\pi}/18)\langle N_{Re}\rangle\left(\frac{\rho_p}{\rho}\right)\left(\frac{2d}{\lambda}\right)$. This result is shown in Fig. 2.5. Although we cannot obtain exact information about the Lagrangian or Eulerian microscale, K is far smaller than 1 for the case of deoxidized particles in a steel melt. Therefore, in the present computation the assumption of $D_p/D \doteq 1$ will be valid.

On the other hand, Kolmogorov assumed that the characteristics of turbulence could be determined by the parameters ν and ε at high Reynolds number. From a dimensional analysis, it follows that [6],

for the length scale $$\eta = \left(\frac{\nu^3}{\varepsilon}\right)^{\frac{1}{4}} \tag{2.2.7}$$

for the velocity scale $$v = (\nu\varepsilon)^{\frac{1}{4}} \tag{2.2.8}$$

Fig. 2.6 shows the Kologorov micro scale length η with respect to the turbulent kinetic energy ε. Since ε is now considered to be less than 100(cm^2/sec^3). η is more than 300μ. As the particle being considered is less than 20μm, the particle size is far smaller than η.

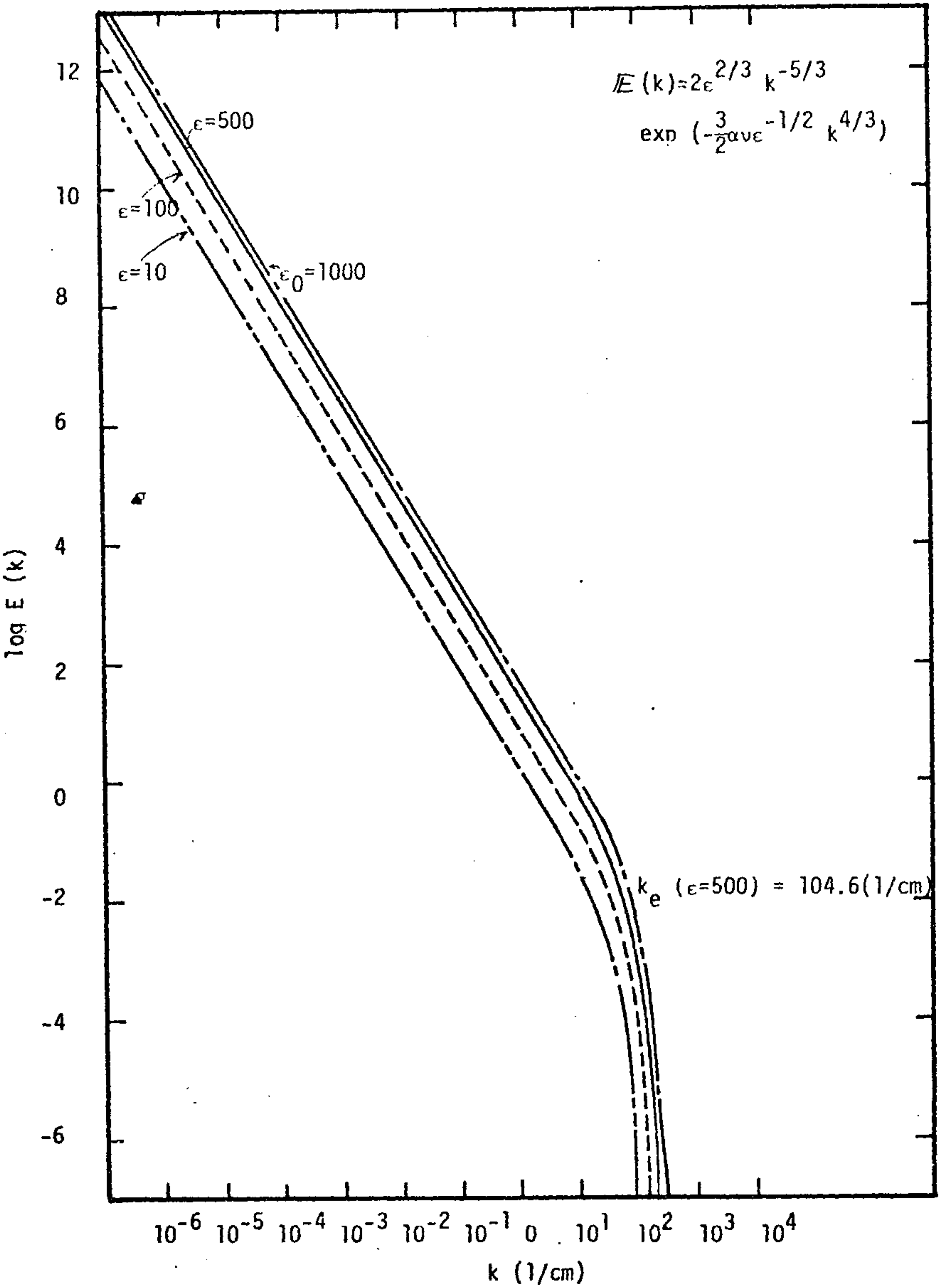


Fig. 2.3 Pao's universal slope law

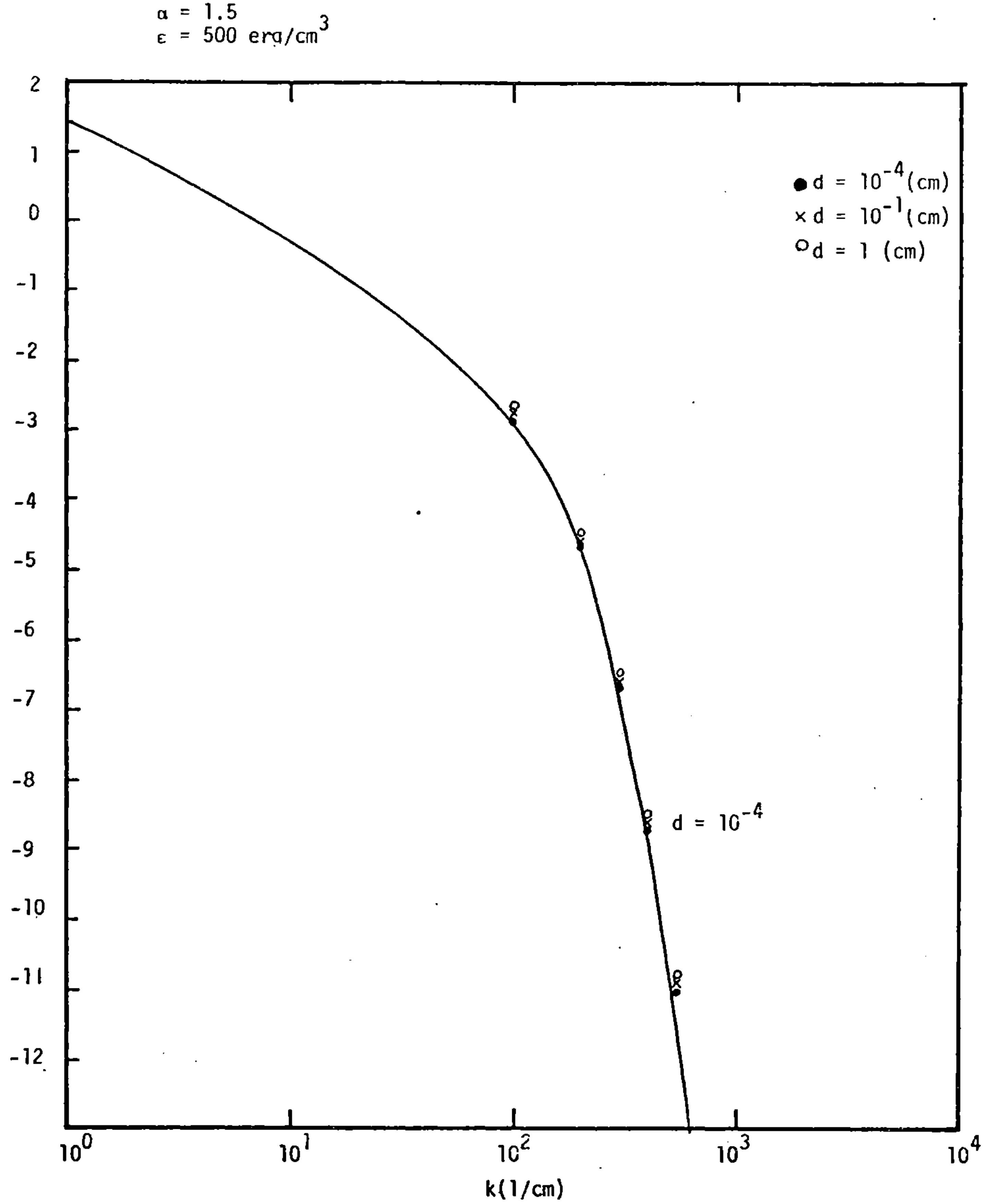


Fig. 2.4 Energy spectrum for fluid and particles

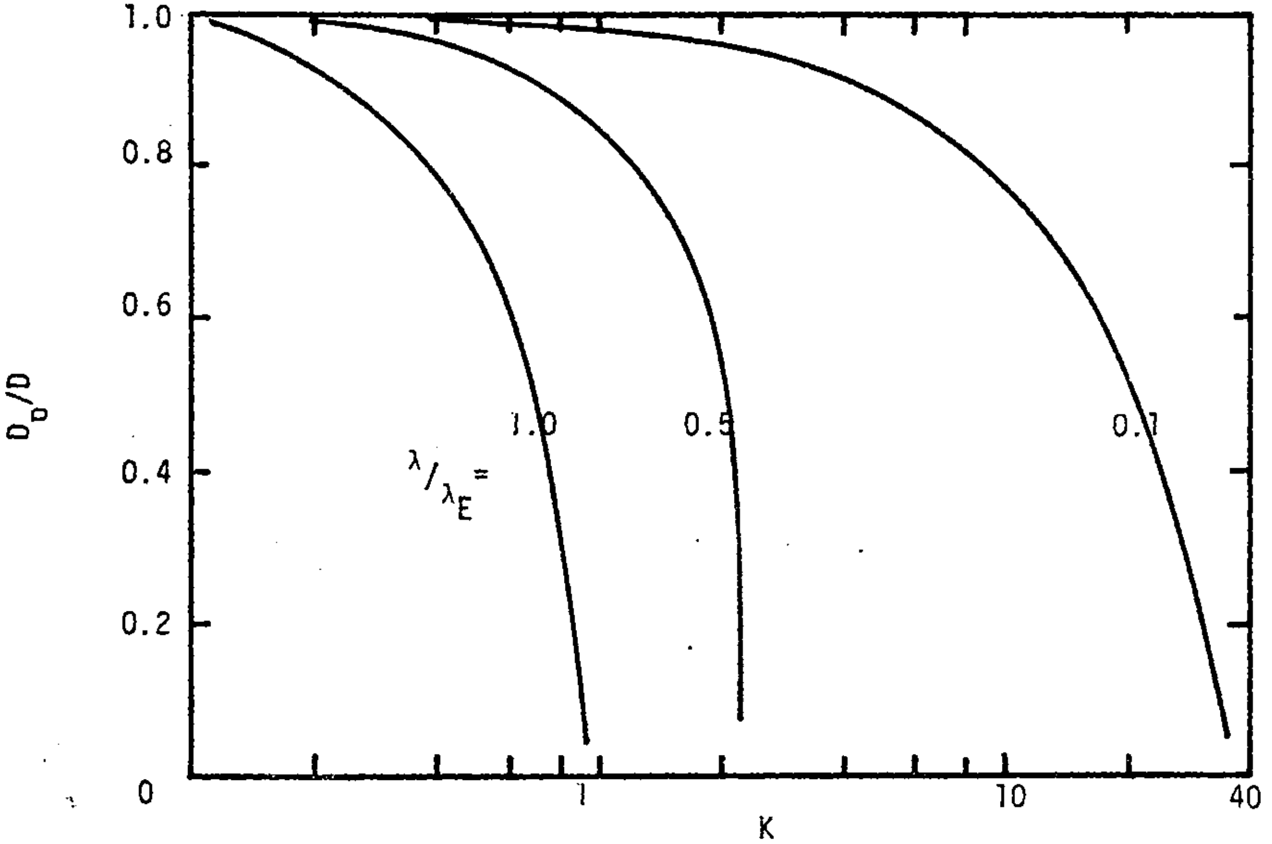
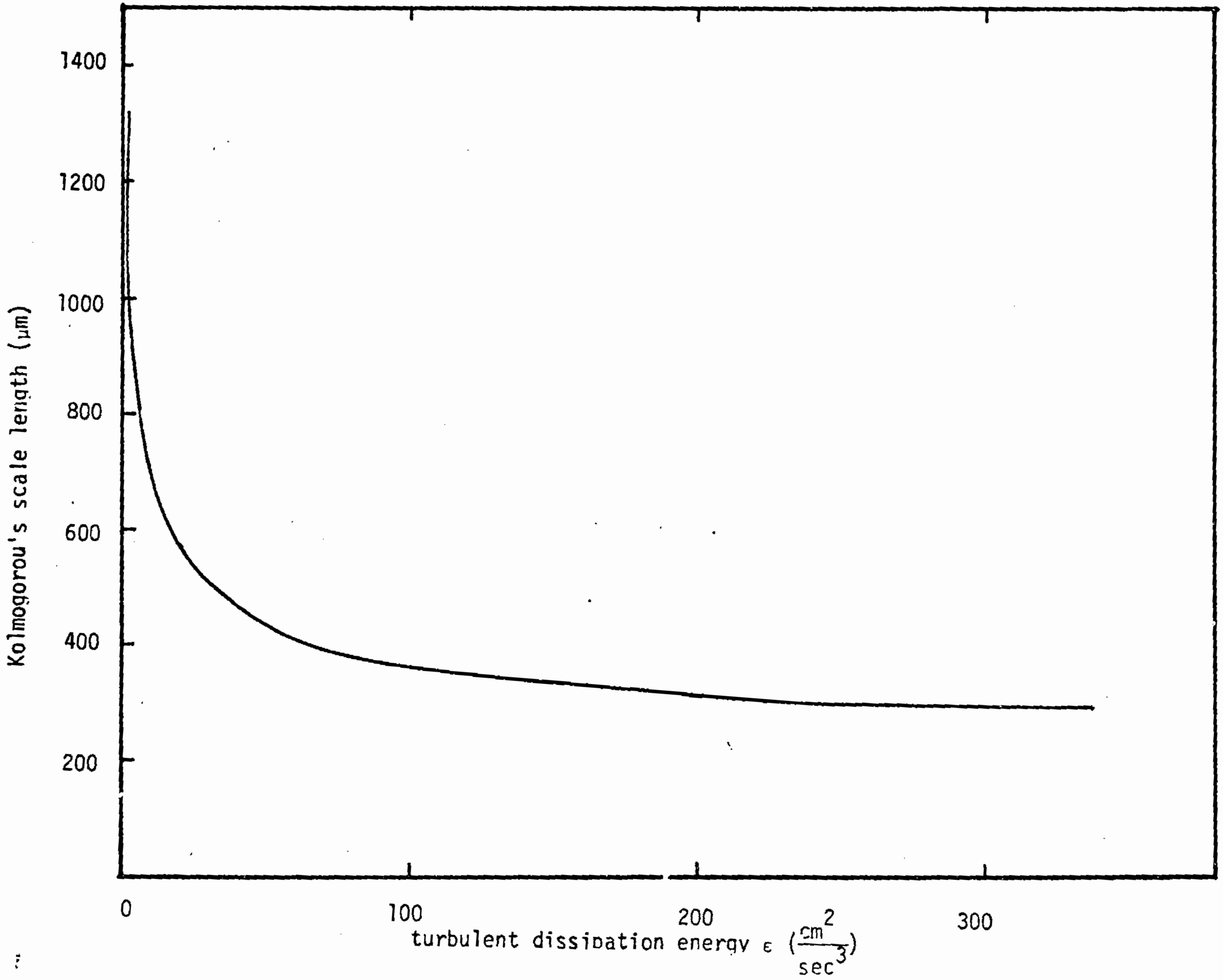


Fig. 2.5 Ratio of diffusivity of particle and turbulent flow (Soo) [12]

Fig. 2.6 Kolmogorov's scale length



2.4 General Expression for Particle Population Balance in Agitated Dispersions

A knowledge of the coalescence and the breakage of second phase particles within a turbulent fluid is important for an understanding of the chemical reactor with a dispersed phase system, and often, population balance concepts are employed to describe the dispersion [27-30]. This theory is often applied to the growth and the breakage of aerosol particles. Although the coalescence function depends largely on the nature of the particles, the general formulation developed by aerosol researchers is valuable for an understanding of the general structure of the problem.

We may define a number density f (ξ, t) of particles in the phase space [27] such that

$f(\xi, t)|d\xi|$ = the number of particles in the system at time t with phase coordinate in the range $\xi_1 \pm 1/2d\xi$, $\xi_2 \pm 1/2d\xi_2$ and introduce the function h (ξ, t) to represent the net rate of addition of new particles into the system.

$h(\xi, t) \cdot |d\xi|$ = the net number of particles introduced into the system per unit time at time t with phase coordinate in the range $\xi_1 \pm 1/2d\xi_1$ $\xi_2 \pm 1/2d\xi_2$

We may consider a small element in the field in order to obtain the convective mass transfer formulation [27].

$$\frac{\partial f}{\partial t} + \sum_i \frac{\partial \{ u_i(\xi t) \cdot f \}}{\partial \xi_i} = h(\xi_i, t) \qquad (2.4.1)$$

Separating the phase coordinate from the external coordinate, we obtain [27]

$$\frac{\partial f}{\partial t} + \sum_i \frac{\partial (u_i f)}{\partial x_i} + \sum_j \frac{\partial \{ G_i(c, \theta, r) \cdot f \}}{\partial r_j} = B(c, \theta, r) \qquad (2.4.2)$$

where β is a nucleation function and G_j is a growth function which depends on the concentration C, the temperature θ, and the dimension of the newly nucleated particles. When the coagulation effect causes only a change in particle distribution (in other words when the nucleation and the diffusional growth can be ignored), the discussion presented above will differ. In this case, we must assume that only two-particle collisions occur in the field. Since no particles are produced by nucleation or diffusional growth, total mass (or total volume) or particles must be conserved at any time. Then,

$$\frac{dm}{dt} = 0 \tag{2.4.3}$$

The number density f (x,m,t) or particles in the space can be described as

$$\frac{\partial f}{\partial t} + \frac{\partial \{v(x,t) f\}}{\partial x} = k(x,m,t) \tag{2.4.4}$$

Here, particle nucleation under the influence of the chemical environment is ignored. Usually agglomeration at x, t between particles of mass m_1 and m_2 is proportional to the product of the number densities f (x,m_1,t), f (x,m_2,t). The proportionality factor is a (x,t). Since mass is conserved during a collision, the number of newly produced particles is [27] [23]

$$\frac{1}{2} a(x,t) \int f(x,m-m',t) f(x,m',t)\, dm' \tag{2.4.5}$$

where the integration extends over all possible values of m'. Similarly, the number or particles which disappear by coalescence at x, t is [2]

$$a(x,t) f(x,m,t) \int f(x,m',t)\, dm' \tag{2.4.6}$$

Then equ. (2.4.2) may be written in explicit form as

$$\begin{aligned} \frac{\partial f(x,m,t)}{\partial t} &+ \frac{\partial \{v(x,t) f(x,m,t)\}}{\partial x} \\ &= a(x,t) \Big[\frac{1}{2} \int f(x,m-m',t) f(x,m',t)\, dm' \\ &\quad - f(x,m,t) \int f(x,m',t)\, dm' \Big] \end{aligned} \tag{2.4.7}$$

When the effect of breakage of particles can no longer be ignored, equ. (2.4.7) may be expressed as C.A. Coulaloglou et al. [28] suggested, as

$$\frac{\partial f(x,m,t)}{\partial t} + \frac{\partial\{v(x,t)f(x,m,t)\}}{\partial x} = a(x,t)\left[\frac{1}{2}\int f(x,m-m',t)f(x,m',t)dm' - f(x,m,t)\int f(x,m',t)dm'\right] + \int b(m',m)f(x,m',t)dm - b(m',m)f(x,m',t) \qquad (2.4.8)$$

where b(m',m) is the distribution function of daughter particles produced from breakage of mass m' particles. The generalized form for the mass population balance can be summarized in Table 2.1. Equ. (2.4.8) coincides with the expression employed by U. Lindborg and K. Torsell [23] except for the convection terms.

As mentioned above, the difficulty in calculating the population balance is in the mass balance. One of the earliest expressions of particle coalescence was made by Smoluchowski [31].

$$\frac{dn_1}{dt} = -\alpha_{11}n_1^2 - \alpha_{12}n_1n_2 - \alpha_{13}n_1n_3 - \cdots$$

$$\frac{dn_2}{dt} = \frac{1}{2}\alpha_{11}n_1^2 - \alpha_{12}n_1n_2 - \alpha_{22}n_2^2 - \alpha_{23}n_2n_3 - \cdots$$

$$\frac{dn_3}{dt} = \alpha_{12}n_1n_2 - \alpha_{13}n_1n_3 - \alpha_{24}n_2n_3 - \alpha_{33}n_3^2 - \cdots$$

$$\frac{dn_4}{dt} = \alpha_{13}n_1n_3 + \frac{1}{2}\alpha_{22}n_2^2 - \alpha_{14}n_1n_4 - \alpha_{24}n_2n_4 - \cdots \qquad (2.4.9)$$

However, simple this expression is, it contains a weakpoint hardly acceptable from the view point of mass balance.

Table 2.1 Expression for particle population balance

$$\frac{\partial f}{\partial t} + \sum_{i=1}^{3} \frac{\partial \{V_i f\}}{\partial x_i} + G = B\,(C,\ \theta,\ r) + \alpha\,(x,\ m,\ t) + \beta\,(x,\ m,\ t)$$

J; Number density of particles

G; Growth by diffusion

B; Nucleation

α; Coagulation of particles

β; Breakage of particles

$$G = \sum_j \frac{\partial \{G_j\ (C,\ \theta,\ r)\ f\}}{\partial r_j}$$

$$\alpha\,(x,\ m,\ t) = A\,(x,\ t)\ [\tfrac{1}{2} \int f\,(x,\ m - m',\ t)\ f\,(x,\ m',\ t)\ dm'$$

$$- f\,(x,\ m,\ t) \int f\,(x,\ m',\ t)\ dm']$$

$$\beta\,(x,\ m,\ t) = \int b\,(m',\ m)\ f\,(x,\ m',\ t)\ dm'$$

$$- b\,(m',\ m)\ f\,(x,\ m',\ t)$$

2.5 The Mechanism of Small Particle Coagulation in a Turbulent Flow

In the previous section, the generalized expression for particle population balance was discussed. Another important issue for the analysis of particle coagulation is an estimation of collision frequency in turbulent flow. Most of the studies on this subject were done in relation to meteorology or aerosol behavior. The most instructive studies on the collision frequency in turbulent streams were performed by P.G. Saffman and J.S. Turner.

1) Collision between particles moving with fluid. (by Saffman and J.S. Turner [26]).

Assuming that the mean concentrations of two sizes of particles in a given population be n_1 and n_2 per unit volume, and that their radii be r_1 and r_2 respectively, then the mean flux of fluid into a sphere of radius $R = r_1 + r_2$ surrounding one particle is

$$-\int_{w_r} w_r \, dS \qquad (2.5.1)$$

where w_r is the radial component of the relative velocity. The collision rate is

$$-n_1 n_2 \int_{w_r<0} w_r \, dS \qquad (2.5.2)$$

now, assuming that

$$-\overline{\int_{w_r} w_r \, dS} = \frac{1}{2}\int |w_r| \, dS = 2\pi R^2 |\overline{w_x}| \qquad (2.5.3)$$

then,

$$|\overline{w_x}| = R\,\overline{|\partial u/\partial x|}, \qquad \overline{(\partial u/\partial x)^2} = \epsilon/15\nu$$

and we obtain

$$\begin{aligned} N &= n_1 n_2 (2\pi R^2 \overline{|w_x|}) \\ &= n_1 n_2 \, 2\pi R^3 \left|\frac{\partial u}{\partial x}\right| \\ &= n_1 n_2 (r_1 + r_2)^3 \left(\frac{8\pi^2 \epsilon}{15\nu}\right)^{\frac{1}{2}} \\ &= 2.3\,(r_1 + r_2)^3 n_1 n_2 \left(\frac{\epsilon}{\nu}\right)^{\frac{1}{2}} \end{aligned} \qquad (2.5.4)$$

2) Collision between particles in relative motion with fluid [26].

A more sophisticated analysis was also made by P.G. Saffman and J.S. Turner for particles in motion relative to the surrounding fluid. In this case, the analysis of collision frequency is rather complicated. The collision frequency is derived from encounter probability which depends on the relative velocities between the particles and the fluid surrounding them. The final representation for the collision frequency can be written as

$$N = 2(2\pi)^{\frac{1}{2}} R^2 n_1 n_2 \left[\left(1-\frac{\rho_p}{\rho}\right)^2 (\tau_1-\tau_2)\left(\frac{D\bar{u}}{Dt}\right)^2 + \frac{1}{3}\left(1-\frac{\rho_p}{\rho}\right)(\tau_1-\tau_2)^2 g^2 + \frac{1}{9} R^2 \frac{\epsilon}{\nu} \right]^{\frac{1}{2}} \qquad (2.5.5)$$

where ρ_p, the density of particles

ρ, the density of fluid

ϵ, the turbulent dissipation energy

When the density of particles can be considered to be equal to the density of the fluid, (i.e. $\rho = \rho_p$) the first two terms disappear and equ. (2.5.5) gives

$$N = 1.67 R^3 n_1 n_2 \left(\frac{\epsilon}{\nu}\right)^{\frac{1}{2}} \qquad (2.5.6)$$

Further, in the case when there is no turbulence (i.e. collision by buoyancy force) Equ. (2.5.5) leads to

$$N = \pi R^2 n_1 n_2 g \left(1-\frac{\rho_p}{\rho}\right)(\tau_1-\tau_2) \qquad (2.5.7)$$

As shown later this expression is similar to the representation given by Lindborg and Torsell [19].

Equ. (2.5.6) is used for the calculation of particle coalescenc

3) Levich's collision theory [32].

Levich proposed two types of collision; (1) gradient collision, (2) turbulent collision. For the gradient collision of two particles with radii r_1 and r_2, the total number of encounters is represented by

$$N_{grad} = \frac{32}{3} n_0^2 \Gamma R^3 = \frac{4}{3} \mathrm{grad}\, v \,(r_1 + r_2)^3 n_1 n_2 \qquad (2.5.8)$$

where Γ is the velocity gradient in the fluid. This is essentially similar to Saffmen's first case (e.g. equ. (2.5.4)) except for the coefficient.

On the other hand, Levich derived the expression for turbulent collisions as follows:

$$N_{turb} = 12\pi\beta \sqrt{\frac{\varepsilon_0}{\nu}}\, R^3 n_0^2 \qquad (2.5.9)$$

This expression is also similar to Saffman's representation except for the coefficient.

4) Collision model by U. Lindborg and K. Torsell [19].

U. Lindborg and K. Torsell derived a collision model based on both Stokes' collision and gradient collision theory.

Their Stokes collision model comes from equ. (2.5.7). The Stokes' force can be written in an explicit form as

$$\tau = \frac{2r^2(\rho - \rho_p)}{9\mu} \qquad (2.5.10)$$

substituting this into equ. (2.5.7) gives

$$\begin{aligned} N &= \pi R^3 n_1 n_2 g \left(1 - \frac{\rho_p}{\rho}\right) \frac{2(\rho - \rho_p)}{2\mu} \left| r_1^2 - r_2^2 \right| \\ &= k \left| r_1^2 - r_2^2 \right| (r_1 + r_2)^2 n_1 n_2 \\ &= k \left| r_1 - r_2 \right| (r_1 + r_2)^3 n_1 n_2 \end{aligned} \qquad (2.5.11)$$

where k is 7.2 for SiO_2 particles in steel melt according to Lindborg and Torssell.

For the gradient collision model, Levich expressed the velocity gradient in explicit parameters as;

$$\mathrm{grad}\, v = \frac{v_e^{\frac{3}{2}}}{\nu^{\frac{1}{2}}\; \ell^{\frac{1}{2}}} \quad \text{for the interior of the bath}$$

$$(2.5.12)$$

$$\mathrm{grad}\, v = \frac{5 v_e}{\ell} \quad \text{for the boundary layer}$$

Finally, adding both terms, Lindborg obtained the following for gradient collision

$$\mathcal{N} = \frac{4}{3}(r_1 + r_2)^3 \left(\frac{5 v_\ell}{\ell} + \frac{9 v_\ell^{\frac{3}{2}}}{\nu^{\frac{1}{2}} \ell^{\frac{1}{2}}} \right)$$

A summary of the coagulation models in turbulent flow is listed in Table 2.2.

Table 2.2 Models of particles coalescence

Saffman and Turner (moving with air)	$N = n_1\ n_2\ (R_1+R_2)^3 \sqrt{\frac{8\pi^2 \varepsilon}{15\nu}} = 1.3\ n_1\ n_2\ (R_1+R_2)^3 \times \sqrt{\frac{\varepsilon}{\nu}}$
Saffman and Turner (moving relatively)	$N = 2(2\pi)^{1/2}\ R^2\ n_1 n_2\ [(1-\frac{\rho}{\rho_o})^2\ (\tau_1-\tau_2)^2\ (\frac{Du}{pt})^2 + \frac{1}{3}\ (1-\frac{\rho}{\rho_o})^2\ (\tau_1-\tau_2)^2 g^2 + \frac{1}{9}\ R^2\ \frac{\varepsilon}{\nu}]^{1/2}$ when the first two terms are zero $N = \frac{2}{3}\ R^3\ n_1 n_2\ (\frac{2\pi\varepsilon}{\nu})^{1/2}$ $= 1.67\ R^3\ n_1 n_2\ (\frac{\varepsilon}{\nu})^{1/2}$
Levich (Brownian)	$N = 8\pi Da\ n_o^2$
Levich (Turbulence)	$N = 12\pi\beta\ R^3 n_o^2 \sqrt{\frac{\varepsilon_o}{\nu}}$
Lindborg and Torsell (stokes')	$N = 7.2\ \lvert r_1-r_2 \rvert\ (r_1+r_2)^3\ n_1 n_2$
Lindborg and Torsell (Turbulence)	$N = \frac{4}{3}\ (r_1+r_2)^3\ (\frac{5V_\ell}{\ell} + \frac{V_\ell^{3/2}}{\nu^{1/2}\ \ell^{1/2}})\ n_1 n_2$
Scaninject	$N = 1.3\ (R_1+R_2)^3\ n_1 n_2 \sqrt{\frac{\varepsilon}{15\nu}}$

2.6 The Mechanism of Small Particle Deposition from Turbulent Flow to a Wall

As shown in the previous section, particle motion in turbulent streams may be described by equ. (2.2.1). However, the movement of particles in the laminar boundary layer is determined mainly by the lift force induced in viscous shear flow. Saffman [33] derived the lift force as follows:

$$F_L = \frac{K\mu \bar{U} a^2}{\nu^{\frac{1}{2}}}\left[\frac{du}{dy}\right]^{\frac{1}{2}} \qquad (2.6.1)$$

where $\bar{U}$ is difference between the velocity of the particle and the fluid, du/dy is the velocity gradient in the shear flow and K is taken as 81.2. In addition, a Stokes' force acts on the sphere in an opposite direction to the direction of motion.

$$F_S = 6\pi\mu d_p \bar{V} \qquad (2.6.2)$$

where d_p is the particle radius

V is the relative velocity of the particle.

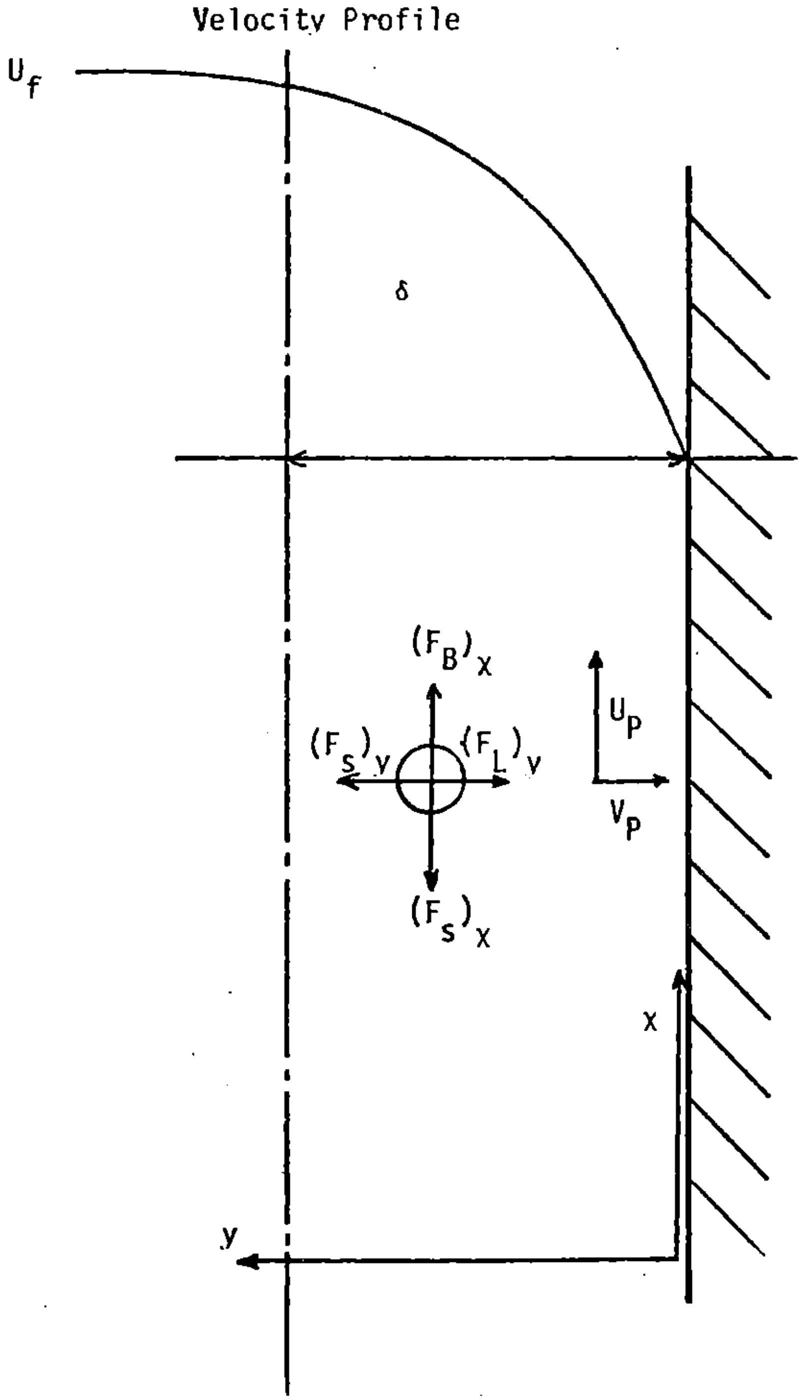
All of the forces acting on a particle in a laminar boundary layer are represented schematically in Fig. 2.7. P.O. Rouhianan and T. W. Stachiewicz [34] proposed a simple governing equation for the particle motion in the boundary layer

$$-3\pi\mu d_p(u_p-u_f)-\frac{\pi}{6}d_p^3(\rho_p-\rho_f)g=\frac{\pi}{6}\rho_p d_p^3\frac{du_p}{dt} \qquad (2.6.3)$$

$$-3\pi\mu d_p v_p-\frac{K\mu(u_p-u_f)}{4}\left(\frac{du}{dy}\right)^{\frac{1}{2}}\frac{d_p^2}{\nu^{\frac{1}{2}}}=\frac{\pi}{6}\rho_p d_p^3\frac{dv_p}{dt} \qquad (2.6.4)$$

where subscripts p and f denote particle and fluid, respectively. These equations can be regarded as a force balance on the particle in the direction of x and y. The second term of equ. (2.6.4) is the shear lift term posed by Saffman [33].

The velocity distribution along the flat wall can be described by Karman's linear approximation. At the nearest region to the wall, which is



$$(F_L)_y = \frac{K_u V_a}{\nu^{\frac{1}{2}}} \left[\frac{du}{dy}\right]^{1/2}$$

$$(F_s)_y = 6\pi\mu a \, (U_p - U_f)$$

$$(F_s)_x = 6\pi\mu a V_p$$

$$(F_B)_x = \frac{4\pi}{3} a^3 \, (\rho_p - \rho_f)_g$$

Fig. 2.7 Schematic representation of forces acting on a particle in a boundary layer expressed as

$$v^+ = y^+ \qquad 0 < y^+ < 5 \qquad (2.6.5)$$

, so that

$$\frac{v}{\sqrt{\tau_0/\rho}} = \frac{y}{\nu}\sqrt{\frac{\tau_0}{\rho}}$$

then

$$u = \frac{y}{\nu}\frac{\tau_0}{\rho} = \frac{y^2}{\nu}V\frac{f}{2}$$

and

$$\frac{\partial u}{\partial y} = \frac{V^2}{\nu}\frac{f}{2}$$

where f is the friction factor

V is the fluid velocity at the edge of the sublayer.

Then, if we assume a value for the y-direction, velocity at the edge of sublayer, we can solve equations (2.6.3) and (2.6.4) and find the trajectory of a particle. Although P.O. Rouhianinen et al. [34] considered only the case of an air-solid particle system, it could be extended to the general concept of a particle deposition system.

On the other hand, mass-transfer coefficient approaches were made by S.K. Friedlander etal. [35] and J.T. Davis [38]. The advantage of this approach is that mass-transfer coefficient type description is convenient for the over-all computation of particle concentration in the vessel.

Generally speaking, the kinematic viscosity near the wall can be calculated, by taking

$$\nu_F = \tilde{v}_y' l = \tilde{v}_y' c y$$

on the other hand,

$$\tilde{v}_y' = \eta v_0 \qquad \text{at } y = \delta_1$$

then

$$\tilde{v}_y' = -\int (\partial \tilde{v}_x/\partial x)\,dy$$
$$= y^3 \eta v_0/\delta_1^2$$
$$= c y^3 \eta v_0/\delta_1^2 \qquad (2.6.8)$$

therefore

$$\nu_E/\nu = c y_+^3 (\eta/25) \qquad (2.6.9)$$

A reasonable fit with experimentally determined velocity distributions of velocity near the wall is obtained of $c\eta/25 = \frac{1}{250}$.

Davis [38] suggest that at the turbulent core equ. (2.6.9) can be written as

$$\nu_E/\nu = (y^+/8.9)^3 \qquad (2.6.10)$$

Lin et al. [39] suggests

$$\nu_E/\nu = (y^+/14.5)^3 \qquad (2.6.11)$$

for the particles used in the present calculation the rate of transfer can be expressed as

$$j = -D_E\, \partial\bar{c}/\partial y \qquad (2.6.12)$$

Combining (2.6.10) and (2.6.12) and assuming the Reynolds analogy at $y+ > 0$, Davies [38] obtained the mass transfer correlation.

$$\frac{k}{V} = \frac{\frac{f}{2}}{1+\sqrt{\frac{f}{2}}\left[\frac{353}{S^{+2}} - 19\right]} \qquad (2.6.13)$$

On the other hand, Friedlander et al. [35] obtained the following form:

$$\frac{k}{V} = \frac{\frac{f}{2}}{1+\sqrt{\frac{f}{2}}\left(\frac{1523}{S^{+2}} - 50.6\right)} \qquad (2.6.14)$$

where

$$S^+ = \frac{m\tilde{v}_y'}{3\pi\mu d_p}\,\frac{V_0}{\nu}$$

Then, as Davies mentioned in his book [38], the rate-determining factor in the case of the deposition of large aerosol particles is the distance from the surface at which their fluctation momentum can just carry them through the viscous layer.

A simple expression for particle deposition to the wall was proposed by Levich [32]. He analysed the coagulation of two particles caused by the velocity gradient induced by these particles. In the case of particles, the total number of collisions is expressed by

$$N_{grad} = \frac{32}{3} n_0 \Gamma a^3 \qquad (2.6.15)$$

where

$$a = r_1 + r_2$$

$$\Gamma = \frac{\partial v_x}{\partial y}$$

Engh and Lindskog [21] applied Levich's theory to the deposition of oxidize particles on a wall. They also used the mass diffusivity proposed by Davis [38]

$$D_E = \frac{0.29 \times 10^{-2} v_0^3 y^3}{\nu^3} \qquad (2.6.16)$$

Combining equ. (2.6.16) and (2.6.12) using Vo which is calculated from Kolomogrov's law he obtained

$$N_a = V_i(a) \, S \, C_a \qquad (2.6.17)$$

where

S is wall surface area and

$$V_i(a) = \frac{0.29 \times 10^{-2} \varepsilon_0 \nabla a^2}{\nu^2 \rho_0 S}$$

The problem in calculating the deposition rate using Levich's method is that the particle size is independent of the rate of deposition. This assumtion may be valid when we treat the deposition behavior of particles having a wide range of particle size.

Another model of particle deposition was presented by Linder [22] [24] in his modeling work of oxidized particle removal from a stirred vessel

$$\frac{\partial n_p}{\partial t} = A_1 R \cdot 0.01 \frac{\tau_0}{\rho \nu} n_{op} \qquad (2.6.18)$$

This expression may be regarded as a simplified form of equ. (2.6.15) (2.6.18) and is independent of the particle size.

All the models of particle deposition from a turbulent flow are listed in Table 2.3.

Table 2.3 The description for particle deposition to the wall

Friedlander and Johnston	$\frac{k}{V_{av}} = \frac{f/2}{1 + \sqrt{\frac{f}{2}} \left(\frac{1525}{\bar{S}_+^2} - 50.6\right)}$
J.T. Davies	$\frac{k}{Vm} = \frac{f/2}{1 + \sqrt{\frac{f}{2}} \left(\frac{353}{\bar{S}_+^2} - 19\right)}$
Engh and Lindskog	$N_a = Vi\ (a)\ S\ Ca$ $Vi\ (a) = \frac{0.29 \times 10^{-2}\ \varepsilon_o Va^2}{V^2\ \rho_o S}$
Sten Linder	$\frac{\partial np}{\partial t} = Ai.R \cdot 0.01\ \frac{\tau_o}{\rho\mu}\ n_o p$ $= Ai.R \cdot 0.01\ \frac{V^2}{\nu}\ \frac{f}{2}\ n_o p$

2.7 Turbulence Modeling

The equations describing turbulent fluid flow are now presented. Although turbulence phenomena have been studied by many researchers and applied to simple types of flow, it cannot be said that a general expression for turbulence phenomena has been perfected. Still, some modeling methods are very useful and powerfull for predicting these phenomena. Additionally, these techniques may provide an effective means of studying systems which are difficult to investigate experimentally, such as industrial scale reactor.

A turbulence model may be obtained by using the Boussinesq assumption [40].

$$-\rho\overline{u_i' u_j'} = \mu_T\overline{\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)} - \frac{2}{3}\left(\mu_T\frac{\partial \bar{u}_k}{\partial x_k} + \bar{\rho} k\right)\delta_{ij} \qquad (2.7.1)$$

Cartesian tensor notation is utilized in this expression. Bousinesq's assumption seems to be valid under several experimental circumstances. In analogy with the coefficient of viscsity in Stokes' law, Bousinesq introduced the concept of mixing coefficient

$$\tau_T = -\rho\overline{u'v'} = A_\tau\frac{\partial \bar{u}}{\partial y} \qquad (2.7.2)$$

In this equation, the turbulent shear stress is related to the rate of mean strain through an apparent turbulent viscosity.

This assumption cannot be used for calculation unless a relation between A and τ is given.

Based on the number of additional differential equations which are necessary in order to determine the tubrulent characteristics, the turbulence models may be clarrified into four categories based on the number of additional differential equations required to determine the turbulence characteristics [41-43]

1) zero-equation models,

2) one-equation models,

3) two-equation models,

4) multi-equation models.

1) Zero equation models

One of the simplest turbulence models was proposed by L. Prandtl;

$$\mu_T = \bar{\rho}\, l^2 \left| \frac{\partial \bar{u}}{\partial y} \right| \qquad (2.7.3)$$

where ℓ a mixing length. This hypothesis is derived from an analogy to the kinetic theory to gases.

With reasonable accuracy, $l \left| \frac{\partial \bar{u}}{\partial y} \right|$ can be considered to be a characteristic velocity V_T. Then μ_T can be interpreted to be

$$\mu_T = \rho \bar{V}_T\, l \qquad (2.7.4)$$

A typical mixing length distribution is given by van Driest [45]. He assumed that the amplitude of the motion diminishes from the wall according to the factor [exp (-y/A)], and that the factor [1 - exp (-y/A)] must be applied to the fluid oscillation to obtain the damping effect of the wall, then

$$l_m = K y \left[1 - \exp\left(- \frac{y\, \tau_s^{\frac{1}{2}} \rho^{\frac{1}{2}}}{A \mu} \right) \right] \qquad (2.7.5)$$

where A is the damping const, A = 26

2) One-equation models

"One equation models" are models which need the solution of one additional partial differential equation in order to evaluate the Reynolds stress and mass flux term.

Considering Prandtl's mixing length model mentioned earlier, μ_T, may be expressed as $\mu_T = \rho V_T \ell$. Prandtl and Kolmogorov suggested that V_T was proportional to the square root of turbulent kinetic energy, $k = \frac{1}{2}\overline{u_i' u_i'} = (\overline{u'^2} + \overline{v'^2} + \overline{w'^2})/2$ and that μ_t could be expressed as

$$\mu_T = C_k \bar{\rho} \sqrt{k}\, l \qquad (2.7.6)$$

The general transport equation for turbulent kinetic energy is [6]

$$\frac{Dk}{Dt} = \frac{\partial}{\partial x_i} u_i\left(\frac{p}{\rho} + k\right) - \overline{u_i' u_j'}\frac{\partial \bar{u}_i}{\partial x_i} + \nu \frac{\partial}{\partial x_i} \overline{u_j\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)}$$
$$- \nu \overline{\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_j}{\partial x_i}} \qquad (2.7.7)$$

Assuming incompressibility and homogeneous turbulence, equ. (2.7.7) reduces to

$$\rho\frac{Dk}{Dt} = -\frac{\partial}{\partial y}\left(\rho\overline{v'k'} + \overline{v'p'}\right) - \rho\overline{u'v'}\frac{\partial u}{\partial y} - \mu\sum\left(\frac{\partial u_i'}{\partial x_i}\right)^2 \qquad (2.7.8)$$

convective flux = diffusion + production - dissipation

The above exact transport equation can be modeled as [41]

$$\rho\frac{Dk}{Dt} = \frac{\partial}{\partial y}\left(\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial y}\right) + \mu_t\left(\frac{\partial u}{\partial y}\right)^2 - C_D\frac{\rho k^{\frac{3}{2}}}{l} \qquad (2.7.9)$$

3) Two equation models

In the one equation model, μ_T depends only on ℓ, which is characterized as independent of the "flow history".

One of the most frequently used two-equation models is the model of Jones and Launder.

In this model ε is assumed to be related to other model parameters by $\varepsilon = Ck^{3/2}/\ell_\varepsilon$ where $\ell\varepsilon$ is referred to as the dissipation length and C is constant. Then the turbulent viscosity is

$$\mu_T = C_\mu \bar{\rho}\, k^2/\varepsilon = c'\rho k^{\frac{1}{2}} \ell_\varepsilon \qquad (2.7.10)$$

At high Reynolds number, the transport equation for ε may be expressed as;

$$\rho\frac{D\varepsilon}{Dt} = \frac{\partial}{\partial x_k}\left[\frac{\mu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_k}\right] + \frac{C_1\mu_t}{\rho}\left(\frac{\partial u_i}{\partial x_k} + \frac{\partial u_k}{\partial x_i}\right)\frac{\partial u_i}{\partial x_k} - C_2\frac{\varepsilon^2}{k}$$
$$(2.7.11)$$

For two dimensional incompressible flow

$$\rho \frac{D\varepsilon}{Dt} = \frac{\partial}{\partial y}\left(\frac{\mu_T}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial y}\right) + \frac{C_1 \mu_T \varepsilon}{k}\left(\frac{\partial u}{\partial y}\right)^2 - \frac{C_2 \rho \varepsilon^2}{k} \qquad (2.7.12)$$

where typical values of the model constants are [44] [41]

C_u	C_1	C_2	σ_k	σ_ε	σ_T
0.09	1.44	1.92	1.2	1.3	0.9

4) Multi-equation models

The multi-equation models need more variables than k and ε. For additional transport parameters, shear stress, normal stress, or higher correlations are used. An overall discussion of this subject is given in the book by Launder and Spalding [41].

2.8 Numerical Methods

Several numerical methods have been proposed to compute fluid flow phenomena. The finite-difference method is the most popular and advanced one. Using several kinds of finite-difference scheme and pressure correction equations, powerful numerical procedures have been developed by the researchers at Imperial College.

Initially, they developed the stream function-vorticity program and this has been copied and applied to fundamental and practical engineering problems. However, it has become apparent that the ω-ϕ method is unsuitable for advanced flow problems. One weak-point of this method is its incapability to calculate a fluid flow field which has a pressure gradient.

A few years later a new program was developed by Pun and Spalding [46]. In stead of vorticity-stream function, "primitive-variables" such as velocities and pressure are used in this program. Additionally, this simplicity makes it possible to develop more sophisticated programs such as three-dimensional flow or mass transfer including chemical reactions.

Chapter 3 FORMULATION OF MATHEMATICAL MODEL

In this chapter, a mathematical model is developed to describe flow and particle coagulation phenomena in R-H degassing system. A short description of the R-H degassing system is presented first and then the formulation of the mathematical model is discussed.

3.1 Description of the R-H Degassing System

A R-H degasser, consists of two parts, a ladle and a vacuum vessel. After it is set under the vacuum vessel the ladle is lifted so as to immerse the twin legs of the vacuum vessel. Then the vacuum vessel is evacuated down to ~ 1 mmHg. Due to atmospheric pressure the level of the molten steel is raised about 1.3m above the surface of the ladle. Innert gas is injected into one leg (called the up-leg) and a recirculating flow through the vacuum vessel and ladle occurs as a result of the apparent difference of density between the up-leg and down-leg side. When the molten steel is exposed to the vacuum atmosphere, the gaseous impurities are released from the melt as a result of the decrease of solubility.

3.2 Assumptions Made in the Model

The physical model of the R-H vacuum process and appropriate coordinate system is shown in Fig. (3.1). The present model is limited to the fluid flow and particle coagulation in the ladle.

The assumptions made about the fluid flow field are as follows:

1) Two-dimensional coordinates may be applied to the flow and particle coagulation model.
2) Since the flow soon becomes steady state, time independent differential equation may be applied to the calculation of fluid field parameters.
3) The existence of slag on the surface may be neglected, therefore for the boundary condition of the top surface a free surface condition is applied.
4) It is assumed that neither the up-leg nor the down-leg is actually immersed in the molten metal.
5) The vertical velocities of the metal through the two legs are deduced from experimentally determined values.

The assumptions made to represent particle coagulation are as follows:

1) Although the particle coagulation system is assumed to be transient, the steady stale flow field parameters may be used.
2) In the present computation, particle sizes are classified into ten Classes (i.e. 2μm to 20μm, every 2μm).
3) The initial particle distribution is calculated from some reports which measured precise particle distributions.
4) The initial particle distribution is uniform in each class.
5) The wall function for particle deposition is derived from equation (2.6.14) which was proposed by Fridlanderand Johnston [35].

6) It is assumed that particle growth is caused only by coagulation as a result of the extremely low rate of diffusional growth and nucleation. Also, it is assumed that the bulk concentration of oxygen or oxidizer is so small that it does not affect the particle growth. (This assumption will be discussed the later in this chapter).

3.3 Governing Equations for Flow Phenomena in the Ladle

The equations describing fluid flow and mass transfer phenomena are now presented. Turbulent motion and mass transfer in the system are represented by the time-smoothed equation of motion and mass. The general transport equation in a two dimensional coordinated system can be written as:

$$\frac{\partial(\rho\phi)}{\partial t}+\underbrace{\frac{\partial}{\partial x}(\rho u\phi)+\frac{\partial}{\partial y}(\rho v\phi)}_{\text{convective term}}-\underbrace{\frac{\partial}{\partial x}\left(\Gamma_\phi\frac{\partial\phi}{\partial x}\right)-\frac{\partial}{\partial y}\left(\Gamma_\phi\frac{\partial\phi}{\partial y}\right)}_{\text{diffusion term}}=\underbrace{S_\phi}_{\text{sourct term}} \qquad (3.3.1)$$

where

x,y	are the coordinates,
u	is the x-direction component of the velocity vector,
v	is the y-direction component of the velocity vector,
ρ	is the density of the fluid,
ϕ	is the general variable and takes the value of 1 for the continuity equation,
Γ_ϕ	is the diffusion coefficient for the variables,
S_ϕ	is the source term for the variable
ϕ	can stand for a variety of differential

quantities, such as the mass fraction of a chemical species, the enthalpy or the temperature, a velocity component, the turbulent kinetic energy, or the turbulent dissipation energy. Additionally an appropriate meaning will have to be given to the diffusion coefficient Γ_ϕ and the source term S_ϕ.

3.3.1 Fluid Flow Equations

1) Equation of Continuity

If a value of unity is assigned to the general variable ϕ and zero is assigned to the source term S_ϕ, eqn. (3.3.1) leads to the continuity equations.

$$\frac{\partial}{\partial x}(\rho u)+\frac{\partial}{\partial y}(\rho v)=0 \qquad (3.3.2)$$

2) Equation of Motion

The general variable ϕ stands for the velocity component u or v. In this case, the diffusion coefficients Γ_u and Γ_v are equal to the effective viscosity μ_{eff} which is the summ of the molecular viscosity μ and the turbulent viscosity μ_t,

$$\mu_{eff} = \mu + \mu_t \qquad (3.3.3)$$

The source terms Su and Sv contain terms associated with viscosity, pressure gradient, and velocity gradient.

The source term Su for the momentum equation in X-direction is [46]:

$$S_u = -\frac{\partial P}{\partial x} + \frac{\partial}{\partial x}\left(\mu_{eff}\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu_{eff}\frac{\partial v}{\partial y}\right) - \rho g_x \qquad (3.3.4)$$

where p is the time-smoothed static pressure

μ_{eff} is the effective viscosity

g_x is the X-directional gravity coefficient

The sum of the static pressure gradient and gravitational force can be cancelled out. However, a pressure difference caused by the velocity field may occur. This pressure, called "pressure correction", is discussed in a later section [46, 47]. In the present case, isothermality is assumed so that the density is constant over the entire field.

Similarily, the source term S_v for the momentum equation in y-direction is represented as

$$S_v = -\frac{\partial P}{\partial y} + \frac{\partial}{\partial x}\left(\mu_{eff}\frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu_{eff}\frac{\partial v}{\partial y}\right) \qquad (3.3.5)$$

3) Transport Equation for Turbulent Properties

The concept of effective viscosity invented by Bousinesq was discussed in the previous section. The effective viscosity is the sum of a molecular viscosity and a turbulent viscosity. Although the molecular viscosity is a characteristic value of the fluid, the turbulent viscosity depends on the fluid motion and on the flow "history". In the present work a two-equation known as k-ε model is used,

where $k = \frac{1}{2}\sqrt{u'^2 + v'^2 + w'^2}$, is the kinetic energy to turbulence

ε = rate of dissipation of k per unit mass.

In this model the turbulent viscosity is related to k and ε by

$$\mu_t = C_D \rho k^2/\varepsilon$$

where C_D is a content. ε may also be expressed as

$$\varepsilon = k^{3/2}/\ell$$

where ℓ is a characteristic length scale of turbulence. Although this model contains some "vagueness", several comparisons between calculation and experiment seem to support its validity. Additionally these equations contain several constants which must be determined experimentally, but, as Spalding [44] mentioned, these constants vary little from one situation to another, so that they can be regarded to a certain extent as "universal". This simplicity makes the calculation of turbulence fields much easier, and especially in the engineering field, this model gives attractive insight into industrial scale reactor problems.

Transport Equations for k

The general variable ϕ stands for the kinetic energy of turbulence k. The differential transport equation can be written as:

$$\frac{\partial}{\partial x}(\rho u k) - \frac{\partial}{\partial y}(\rho v k) - \frac{\partial}{\partial x}\left(\Gamma_k \frac{\partial k}{\partial x}\right) - \frac{\partial}{\partial y}\left(\Gamma_k \frac{\partial k}{\partial y}\right) = S_k \qquad (3.3.8)$$

where

$$S_k = G - D$$

The generation term;

$$G = \mu_T \left[2\left\{ \left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 \right\} + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 \right] \qquad (3.3.9)$$

dissipation term

$$D = \rho \varepsilon$$

and turbulent viscosity

$$\mu_t = \mu_{eff} - \mu_{lam} = c \rho k^2/\varepsilon \gg \mu_{lam}$$

The diffusion coefficient for turbulent energy Γ_k is supposed to be a property of the turbulence similar in magnitude to the effective viscosity

$$\Gamma_k = \frac{\mu_{eff}}{\sigma_k} \qquad (3.3.10)$$

where σ_k is turbulent Prandtl number for the kinetic energy.

Transport Equation for ε

The general variable ϕ stands for the turbulent dissipation ε. The differential transport equation can be written as

$$\frac{\partial}{\partial x}(\rho u \varepsilon) + \frac{\partial}{\partial y}(\rho v \varepsilon) - \frac{\partial}{\partial x}\left(\Gamma_\varepsilon \frac{\partial \varepsilon}{\partial x}\right) - \frac{\partial}{\partial y}\left(\Gamma_\varepsilon \frac{\partial \varepsilon}{\partial y}\right) = S_\varepsilon \qquad (3.3.11)$$

where $S_\varepsilon = C_1 \frac{\varepsilon}{k} G - C_2 \rho \frac{\varepsilon^2}{k}$

and G is a generation term which is mentioned above, and Γ_ε is a diffusivity for turbulent dissipation energy described as

$$\Gamma_\varepsilon = \frac{\mu_{eff}}{\sigma_\varepsilon} \qquad (3.3.12)$$

σ_ε is the Prandtl Number for turbulent dissipation energy. Prandtl numbers for both k and ε are regarded to be in the vincinity of unity.

3.4 Boundary Conditions

In this section, the boundary conditions used for the fluid flow field are presented. The schematic boundary surfaces are shown in Fig. 3.1.

Boundary conditions for the present problem are classified into three categories, wall, free surface, and given velocity (i.e. up-leg and down-leg) boundaries. With reference to Fig. 3.1 the boundary conditions are as follows:

1) At $x=0,\ 0<y<y_1,\ y_2<y<y_3,\ y_4<y<y_5$ (at free surface)

$$U=\frac{\partial V}{\partial y}=0 \qquad (3.4.1)$$

$$\frac{\partial k}{\partial y}=\frac{\partial \varepsilon}{\partial y}=0 \qquad (3.4.2)$$

2) At $x=0,\ y_1<y<y_2 \quad y_3<y<y_4$ (at given velocity boundary)

$$U=U_{inlet}\ (\text{at } y_1<y<y_2),\quad U=-U_{inlet}\ (\text{at } y_3<y<y_4) \qquad (3.4.3)$$

$$V=0 \qquad (3.4.4)$$

$$k=0.05\times[U_{inlet}]^2 \qquad (3.4.5)$$

$$\varepsilon=C_p k^{3/2}/(0.03R_o) \qquad (3.4.6)$$

where R_o is the radius of the up-leg or down-leg.

3) At $y=0$ or $y=y_5$, $0<x<x_5$ (at wall)

The "no-slip" condition is applied to the velocity at the wall

$$U=V=0 \qquad (3.4.7)$$

$$k=\varepsilon=0 \qquad (3.4.8)$$

At a wall, boundary conditions called "wall-functions" must be included since the transport equations for several fluid dynamic characterestics are derived only for high Reynolds number flows. Close to the solid wall and some other interfaces, there are regions where the local Reynolds number of turbulence ($\equiv k^{\frac{1}{2}}l/\nu$, where $l\equiv k^{3/2}/\nu$) is so small that viscous effects predominate over turbulent ones. The wall functions may be regarded as expressions for the momentum, energy and, mass transfer coefficients in the boundary layer. Therefore, the most appropriate wall-function to the situation should be chosen.

Fig. 3.1 shows the region where "wall-function" should be used. Fig. 3.2 describes the grid spacing along the wall. Now, the shear stress along the wall is uniform from wall to adjacent grid line. Then τ_w may be regarded as a boundary condition for the u and v equations, and enters the generation term for the near-wall k. In the neighbourhood of the wall we can assume proportionality between mixing length and wall distance, so that

$$l = \kappa y \qquad (3.4.9)$$

where κ denotes a deminsionless constant which must be deduced form experiment. On the other hand, according to Prandtl's assumption the turbulent shear stress becomes

$$\tau = \rho \kappa^2 y^2 \left(\frac{\partial u}{\partial y}\right)^2 \qquad (3.4.10)$$

Introducing the friction velocity

$$u_0^* = \sqrt{\frac{\tau_w}{\rho}} \qquad (3.4.11)$$

where τ_w is the shear stress at the wall we obtain

$$u_0^* = \kappa^2 y^2 \left(\frac{du}{dy}\right)^2 \qquad (3.4.12)$$

Integrating equ. (3.4.12), we obtain

$$u = \frac{u_0^{*2}}{\kappa} \ln y + C \qquad (3.4.13)$$

Because we assumed τ = constant, equ. (3.4.13) is only valid in the neighborhood of the wall. Again, introducing the dimensionless distance from the wall, $y^+ = y u_0^* / \nu$ we then modify equ. (3.4.13) to the following form

$$\frac{u}{u_0^*} = \frac{1}{\kappa} \ln y^+ + D_1 \qquad (3.4.14)$$

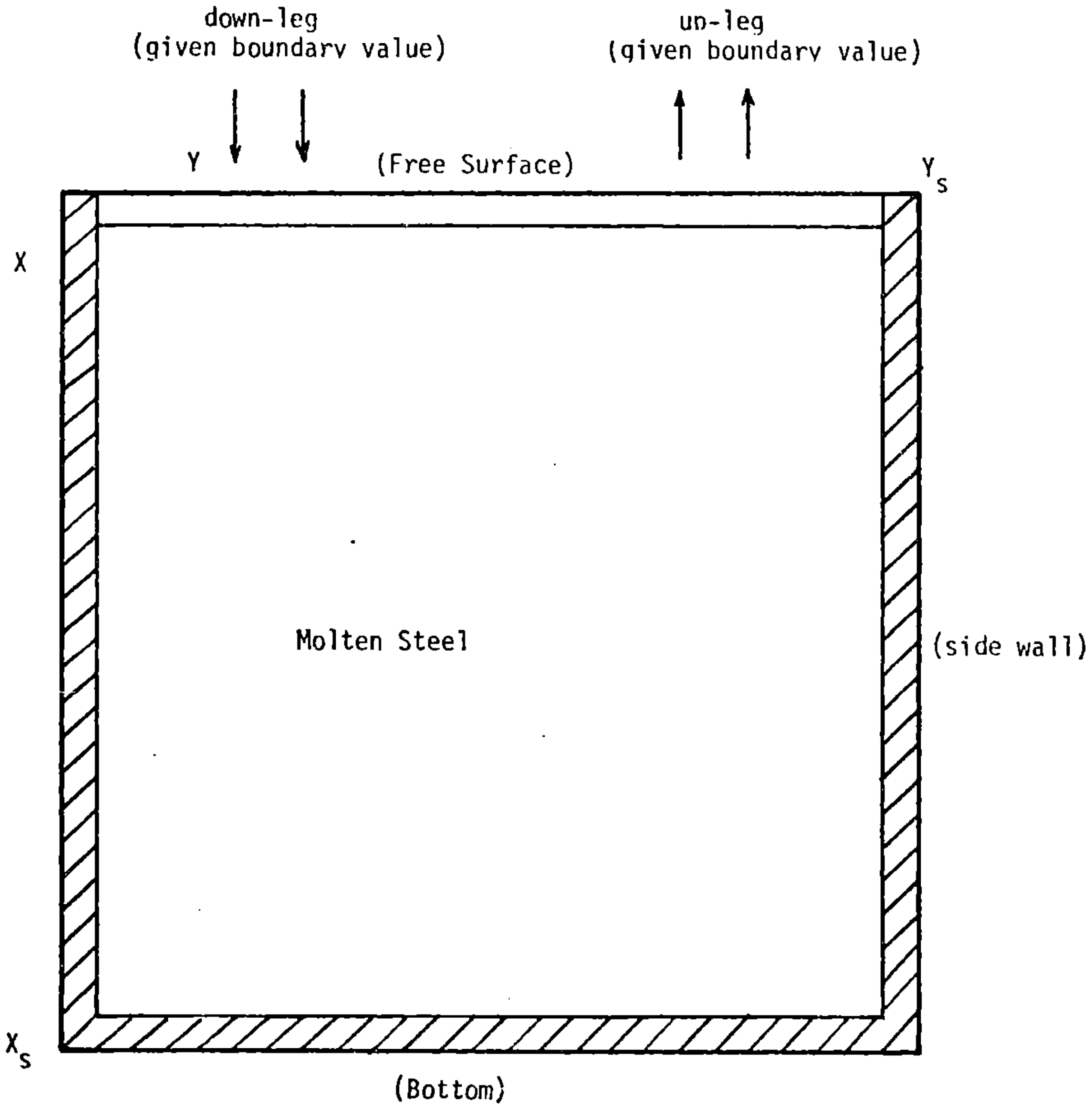


Fig. 3.1 Regions (hatched) for wall function

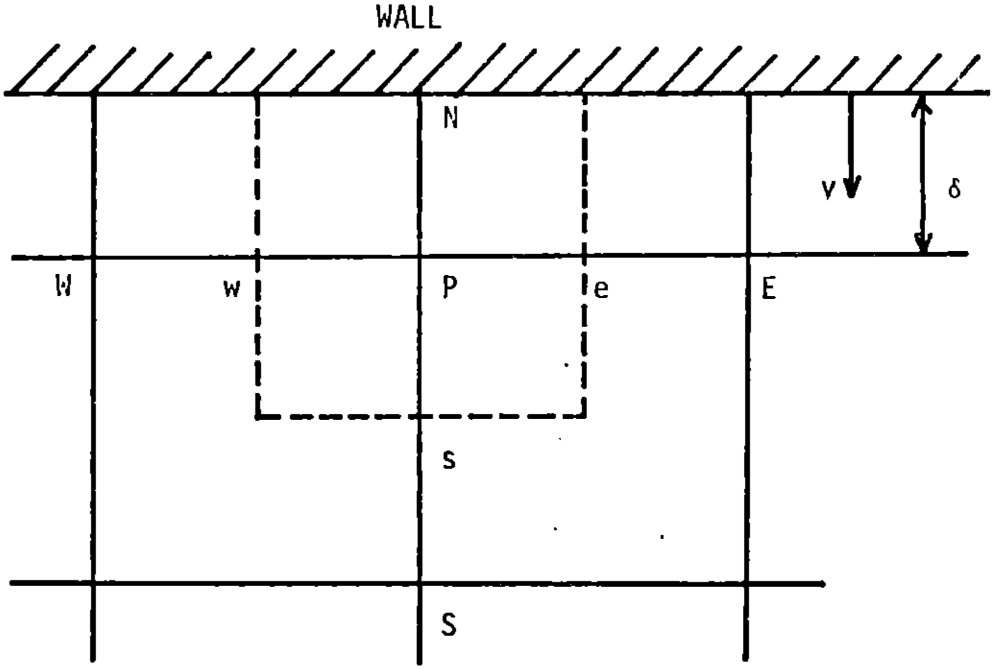


Fig. 3.2 Grid spacing near walls

where k and D_1 are constants which may be determined experimentally, so that

$$A_1 = \frac{1}{K} = 2.5 \qquad D_1 = -\frac{1}{K}\ln\beta \tag{3.4.15}$$

β is determined as 0.111 from the experimental results by Nikuradse. Finally, we obtain the velocity distribution in the wall region as

$$u^+ = \frac{1}{K}\ln(Ey^+) \tag{3.4.16}$$

where E is 9.0.

Equ. (3.4.16) is only valid in the near wall region (i.e. $y^+ < 11.5$). Usually the near wall grid point , P, is sufficiently remote from the wall grid point, w, that the turbulent effects at P totally overwhelm the viscous effects. Spalding proposed the following equation for the momentum flux:

$$\frac{\overline{U}_P}{(\tau/\rho)_w} C_\mu^{\frac{1}{4}} k_P^{\frac{1}{2}} = \frac{1}{K}\ln\left[E y_P \frac{(C_\mu^{\frac{1}{2}} k_P)^{\frac{1}{2}}}{\nu}\right] \tag{3.4.17}$$

here $\overline{U}_p$, τ_w and Y_p are respectively the time average velocity of the fluid at point p along the wall, the shear stress on the wall, and the distance of point p from the wall. This relationship is used as the boundary condition for the velocity.

3.5 General Equations for Particle Transfer and Coagulation

The general equations describing particle transfer and coagulation are now presented. These equations are represented by the time-smoothed equation of mass transfer (particle transfer). The differential equations for particle coalescence are given for each class of size. In the present calculation sizes are classified into ten groups. It is assumed that when the particles grown to the maximum size they float up, so that the concentration of particles larger than the maximum size has no effect on the coagulation behavior of the particles.

Generally the number density f (x,m,t) of particles satisfies the following equation.

$$\frac{\partial f}{\partial t}+\frac{\partial}{\partial x}(uf)+\frac{\partial}{\partial y}(vf)-\frac{\partial}{\partial x}\left(\Gamma_f\frac{\partial f}{\partial x}\right)-\frac{\partial}{\partial y}\left(\Gamma_f\frac{\partial f}{\partial y}\right)+G$$
$$= B(C,\theta,r)+\alpha(x,m,t)+\beta(x,m,t) \qquad (3.5.1)$$

Where G is the growth by diffusion

α (x,m,t) is the coagulation of particles

B (x,m,t) is the rate of nucleation

β (x,m,t) is the breakage of particles

C is bulk concentration of chemical species

θ is temperature

Γ_f is diffusion coefficient for particles.

Now, it is assumed that the growth rates by diffusion and nucleation are ignored and also, the rate of breakage is too small to be considered. Then equ. (3.5.1) can be reduced to

$$\frac{\partial f}{\partial t}+\frac{\partial}{\partial x}(uf)+\frac{\partial}{\partial y}(vf)-\frac{\partial}{\partial x}\left(\Gamma_f\frac{\partial f}{\partial x}\right)-\frac{\partial}{\partial y}\left(\Gamma_f\frac{\partial f}{\partial y}\right)=\alpha(x,m,t) \qquad (3.5.2)$$

here α (x.m,t) maybe defined as

$$\alpha(x,m,t) = \frac{1}{2}\int a(x,m,t) f(x,m-m',t) f(x,m',t)\,dm' - f(x,m,t)\int a(x,m,t) f(x,m',t)\,dm' \qquad (3.5.3)$$

where α (m,x,t) is the rate of collision. Equ. (3.5.3) is an integro-differential equation in particle number density f (x,m,t), and it is difficult to solve explicitly. In order to solve this equation using finite difference methods, it is necessary to establish the discretized equation for each group of particle sizes.

Defining the particle concentration for the ith group of size, C_i, equ. (3.5.2) becomes

$$\frac{\partial(\rho C_i)}{\partial t} + \frac{\partial}{\partial x}(\rho u C_i) + \frac{\partial}{\partial y}(\rho v C_i) - \frac{\partial}{\partial x}\left(\Gamma_{c,i}\frac{\partial C_i}{\partial x}\right) - \frac{\partial}{\partial y}\left(\Gamma_{c,i}\frac{\partial C_i}{\partial y}\right) = S_{c,i}$$
$$(i = 1, \cdots 10) \qquad (3.5.4)$$

where $\Gamma_{c,i}$ is diffusion coefficient of particles of the ith size group.

Strictly speaking, $\Gamma_{c,i}$ depends on the particle size, but, as mentioned in Chapter 2, the dependence of particle diffusivity on size is so small that in the present computation it may be ignored.

Thus $$\Gamma_c = \frac{\mu_{eff}}{\sigma_c}$$

Here σ_c is turbulent Prandtl number for particle diffusivity. This value varies as shown in Fig. 2.5 In the present work a value of 1.0 was employed.

The modeling of the source term is one of the most essential points in this work. The first problem which we will consider is whether two particles colliding at steel making temperatures will rapidly form a single sphere. This effect may depend on the surface energy. Generally, studies performed on silica inclusions show that when two particles collide they usually sinter or coalesce together rapidly to form a single larger sphere [51]. On the other hand, it is reported that primary inclusions other than silica may or may not coalesce after they collide and stick, and that large interconnected clusters form [51].

The various schematic coalescence models are shown in Fig. 3.3. Case I shows that collided particles become a single sphere and Case II shows that they only stick and form clusters. Case III shows the intermediate case between I and II. Although the resultant particles in these three cases have the same volume, the characterestic diameter may differ, so that the behavior in turbulent flow may differ. Smoulchoski's model, discussed in Chapter 2, represents Case II (e.g. clustering). However, if we employ the coagulation derived from Case II, mass conservation is violated. Since the main purpose of this work is to simulate the deoxiation process, this error may not be allowed. Therefore, we employed the assumptions as follows:

1) collided particles immediately form a single sphere
2) only two particles are involved in the collision

Fig. 3.4 - 3.6 show the collided particle sizes in Case I, II and III respectively. In Case II, approximately half of the collided particles grow to a diameter of more than 20μm, which is now considered to be a critical size after the first collision. Therefore, if the coagulation model, Case II, is employed, the rate of particle growth by collision will be much faster than that predicted by the Case I model. However, when collided particles do not form a sperical particle, the Case II or Case III models, represent a better description of the turbulent flow agglomeration process that Case I.

Since present calculations assume the formation of spherical particles after collision, Case I is employed for the coagulation model. The problem is how to treat the source terms so that the mass continuity among each class of size is conserved. For example, when particles of 12μm and 14μm diameter collide with each other a particle of 16.471μm diameter is formed. This particle is located between the 16μm diameter class and 18μm diameter

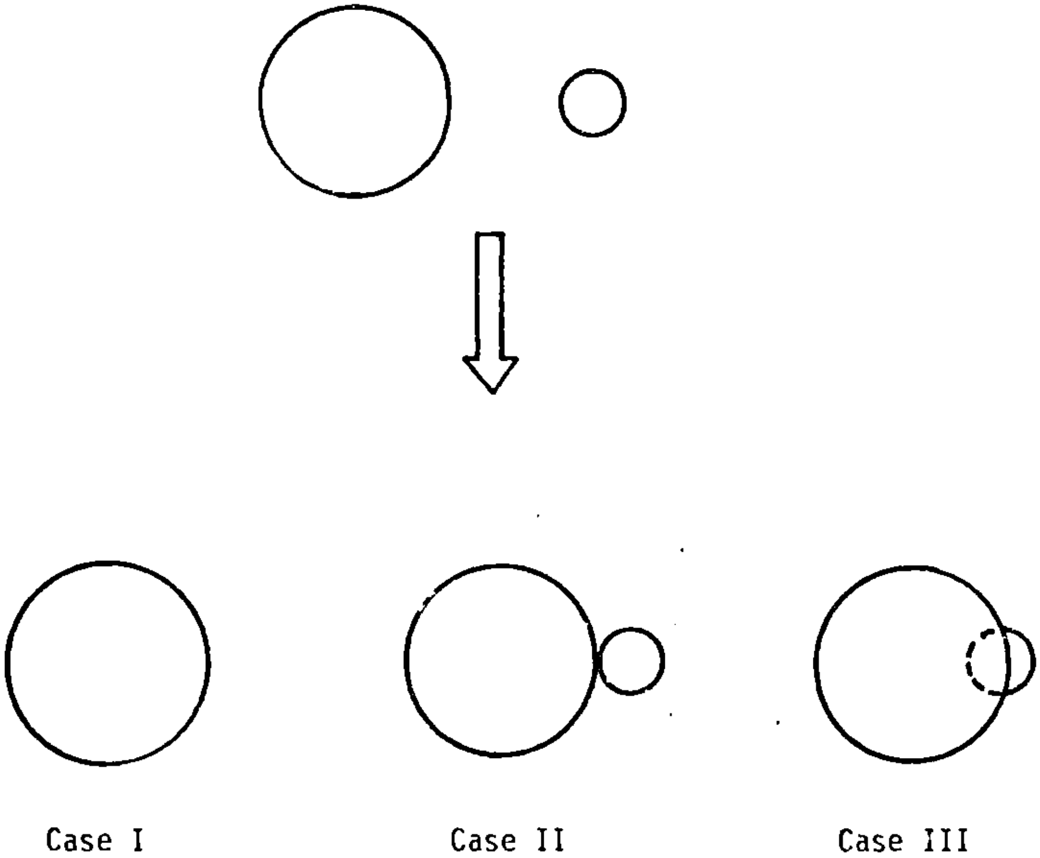
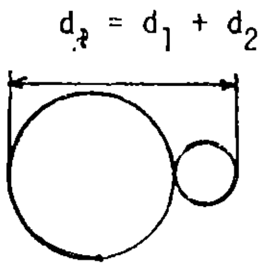


Fig. 3.3 Schematic coalescence models

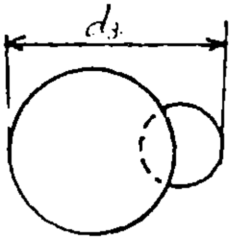
	2	4	6	8	10	12	14	16	18	20
2	2.520	4.160	6.070	8.040	10.027	12.018	14.014	16.010	18.008	20.007
4		5.04	6.542	8.320	10.209	12.146	14.108	16.083	18.066	20.053
6			7.560	8.996	10.674	12.451	14.358	16.276	18.219	20.178
8				10.079	11.478	13.084	14.822	16.641	18.512	20.418
10					12.599	13.973	15.528	17.208	18.975	20.801
12						15.119	16.475	17.992	19.608	21.347
14							17.639	18.982	20.469	22.066
16								21.492	21.492	22.955
18									22.679	24.005
20										25.198

Fig. 3.4 Coalesced particle size for Case I



	2	4	6	8	10	12	14	16	18	20
2	4	6	8	10	12	14	16	18	20	22
4		8	10	12	14	16	18	20	22	24
6			12	14	16	18	20	22	24	26
8				16	18	20	22	24	26	28
10					20	22	24	26	28	30
12						24	26	28	30	32
14							28	30	32	34
16								32	34	36
18									36	38
20										40

Fig. 3.5 Coalesced particle size for Case II



$$d_3 = \frac{(d_1 + d_2) + d_1}{2}$$

	2	4	6	8	10	12	14	16	18	20
2	3	5	7	9	11	13	15	17	19	21
3		6	8	10	12	14	16	18	20	22
6			9	11	13	15	17	19	21	23
8				12	14	16	18	20	22	24
10					15	17	19	21	23	25
12						18	20	22	24	26
14							21	23	25	27
16								24	26	28
18									27	29
20										30

Fig. 3.6 Coalesced particle size for Case III

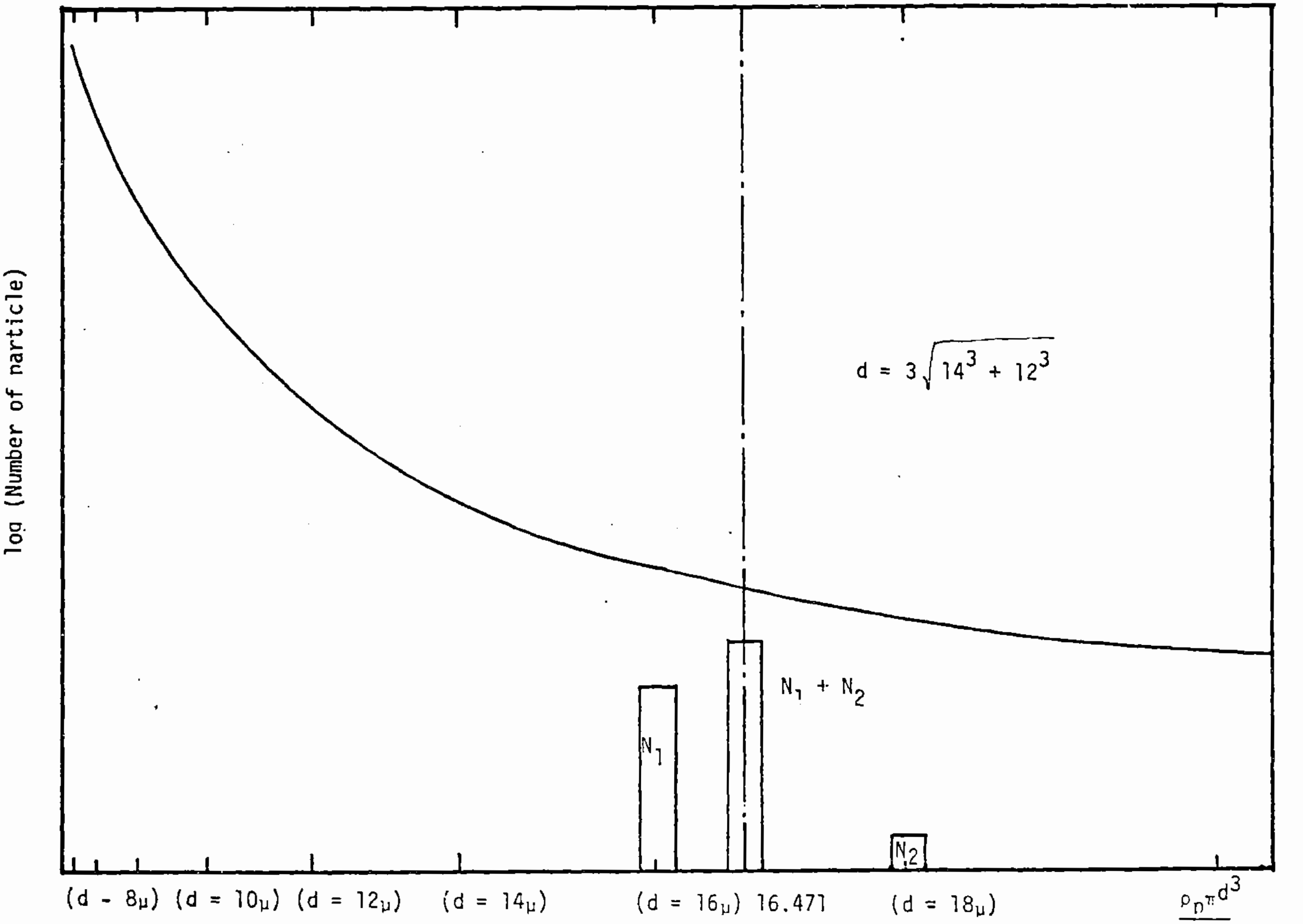


Fig. 3.7 Schematic representation of particle distribution

(μm)

d_2 \ d_1	2	4	6	8	10	12	14	16	18	20
2	2.5198 4 | 0.1648 2 | 0.5522	4.1601 4 | 0.7606 6 | [illegible]	6.0731 6 | 0.9730 8 | [illegible]	8.0403 8 | 0.9837 10 | [illegible]	10.0114 10 | 0.9891 12 | [illegible]	12.0154 12 | 0.9773 14 | 0.0017	14.0032 14 | 0.9782 16 | [illegible]	16.0100 16 | 0.9756 18 | [illegible]	18.0017 18 | 0.9715 20 | 0.0035	20.0061 20 | 0.9773 22 | 0.0027
4		5.0576 4 | 0.5712 6 | 0.4288	6.5420 6 | 0.7884 8 | 0.2116	8.3402 8 | 0.8689 10 | 0.1311	10.2057 10 | 0.9122 12 | 0.0878	12.1661 12 | 0.9371 14 | 0.0629	14.1076 14 | 0.9588 16 | 0.0412	16.0325 16 | 0.9633 18 | 0.0367	18.0651 18 | 0.9707 20 | 0.0293	20.0526 20 | 0.9761 22 | 0.0239
6			7.5546 6 | 0.2704 8 | 0.7296	8.4757 8 | 0.5575 10 | 0.4425	10.6734 10 | 0.7034 12 | 0.2966	12.4502 12 | 0.7875 14 | 0.2125	14.3577 14 | 0.8204 16 | 0.1796	16.2760 16 | 0.8738 18 | 0.1262	18.2190 18 | 0.9006 20 | 0.0994	20.1775 20 | 0.9157 22 | 0.0843
8				10.0791 10 | 0.9071 12 | 0.0929	11.4773 10 | 0.2969 12 | 0.7031	13.0539 12 | 0.4962 14 | 0.5038	14.5212 14 | 0.6215 16 | 0.3785	16.6402 16 | 0.7853 18 | 0.2147	18.5115 18 | 0.7641 20 | 0.2359	20.4173 20 | 0.8069 22 | 0.1931
10					12.5957 12 | 0.7329 14 | 0.2671	13.9724 12 | 0.0166 14 | 0.9834	15.5274 14 | 0.2626 16 | 0.7374	17.2050 16 | 0.4242 18 | 0.5758	18.9765 18 | 0.5586 20 | 0.4414	20.8002 20 | 0.6227 22 | 0.3773
12						15.1186 14 | 0.4736 16 | 0.5264	16.4749 16 | 0.7856 18 | 0.2144	17.9912 16 | 0.0069 18 | 0.9931	19.6458 18 | 0.0235 20 | 0.9765	22.0652 22 | 0.9701 24 | 0.0299
14							17.6384 16 | 0.1984 18 | 0.8016	18.7879 18 | 0.6353 20 | 0.3647	20.4653 20 | 0.7688 22 | 0.2312	22.0652 22 | 0.9701 24 | 0.0299
16								20.1581 20 | 0.9225 22 | 0.0775	21.4919 20 | 0.2722 22 | 0.7278	22.9865 22 | 0.5444 24 | 0.4556
18									22.6771 22 | 0.6806 24 | 0.3194	24.0051 24 | 0.9752 26 | 0.0248
20										25.1916 24 | 0.4605 26 | 0.5395

Fig. 3.8 Collided particle size and the weighting factor for source terms

class (Fig. 3.7). Here the number of particles formed by collision can be calculated from equ. (2.5.6). The calculated number of collided particles may be between the descretized class. The size of collided particles is listed in the upper row in Fig. 3.8. This collided number is divided into each class so as to be inversely proportional to the mass scale. In this way, the sum of mass before collision become equal to that after collision. The coefficient of the weighting function is shown in the middle and the lower row of Fig. 3.8.

The final representation of the source terms is shown in Table 3.1 in an explicit form.

Table 3.1 Governing Equation for Particle Coalescence

$$\frac{\partial n_i}{\partial t} + \frac{\partial}{\partial x}(un_i) + \frac{\partial}{\partial y}(un_i) - \frac{\partial}{\partial x}\left(E\frac{\partial n_i}{\partial x}\right) - \frac{\partial}{\partial y}\left(E\frac{\partial n_i}{\partial y}\right) = S\phi, i$$

$(i = 1, \ldots .\ 10)$

$S\phi,\ i = Su_i + S_{pi},\ n_i \qquad E = \frac{\mu_{eff}}{\rho\sigma_{c,i}}$

$n = 1$

$S_{u,1} = 0.0$

$S_{p,2} = - 0.1428\alpha_{1,1}\ n_1 - \sum_{j=2}^{10} \alpha_{1,j}\ n_j$

$n = 2$

$S_{u2} = 0.1428 \times \frac{1}{2}\, n_1^2$

$S_{p,2} = - 0.0526 \times \alpha_{2,1} \times n_1 - 0.4216 \times \frac{1}{2}\, \alpha_{22}\ \ n_2 - \sum_{j=3}^{10} \alpha_{2,j}\ n_j$

$n = 3$

$S_{u,3} = 0.0526\ \alpha_{2,1}\ n_1\ n_2 + 0.4210\ \frac{\alpha_{22}}{2} \times n_2\ n_2$

$S_{p,3} = - 0.027\ \alpha_{13}\ \ n_1 - 0.2162\ \alpha_{23}\ n_2 - 0.7293\ \alpha_{33}\ n_3 - \sum_{j=4}^{10} \alpha_{3,j}\ n_j$

$n = 4$

$S_{u,4} = 0.027\ \alpha_{31}\ n_3\ n_1 + 0.2162\ \alpha_{23}\ n_3 n_2 + 0.7296\ \frac{\alpha_{33}}{2}\ n_3^2$

$S_{p,4} = - 0.0163\ \alpha_{14}\ n_1 - 0.1311\ \alpha_{24}\ n_2 - 0.4425\ \alpha_{3,4}\ n_3 - \sum_{j=4}^{10} \alpha_{j4}\ n_j$

Table 3.1 (cont'd)

$n = 5$

$$S_{u,5} = 0.0163\ \alpha_{41}\ n_1\ n_4 + 0.1311\ \alpha_{42}\ n_2\ n_4 + 0.4425\ \alpha_{43}\ n_4\ n_3$$

$$+ 0.9671\ \frac{\alpha_{44}}{2}\ n_4\ n_4$$

$$S_{p,5} = -\ 0.0109\ \alpha_{51}\ n_1 - 0.0878\ \alpha_{25}\ n_2 - 0.2966\ \alpha_{35}\ n_3 - 0.7031\ \alpha_{45}\ n_4$$

$$- \sum_{j=5}^{10} \alpha_{5j}\ n_j$$

$n = 6$

$$S_{u,6} = 0.0329\ \alpha_{44}\ \frac{n_4^2}{2} + 0.0109\ \alpha_{51}\ n_5\ n_1 + 0.0878\ \alpha_{52}\ n_2\ n_5$$

$$0.2966\ \alpha_{35}\ n_3\ n_5 + 0.7031\ \alpha_{45}\ n_4\ n_5 + 0.7324\ \frac{n_5^2}{2}$$

$$S_{p,6} = 0.0077\ \alpha_{61}\ n_1 - 0.0629\ \alpha_{62}\ n_2 - 0.2125\ \alpha_{63}\ n_3 - 0.5038\ \alpha_{64}\ n_4$$

$$- 0.9840\ \alpha_{65}\ n_5 - \sum_{j=6}^{10} \alpha_{6j}\ n_j$$

$n = 7$

$$S_{u,7} = 0.2676\ \alpha_{55}\ \frac{n_5^2}{2} + 0.0077\ \alpha_{61}\ n_6\ n_1 + 0.0629\ \alpha_{62}\ n_6\ n_2$$

$$0.2125\ \alpha_{63}\ n_6\ n_3 + 0.5038\ \alpha_{64}\ n_6\ n_4 + 0.9840\ n_6\ n_5 + 0.4736\ \alpha_{66}\ \frac{n_6^2}{2}$$

$$S_{p,7} = -\ 0.0058\ \alpha_{17}\ n_1 - 0.0472\ \alpha_{27}\ n_2 - 0.1596\ \alpha_{37}\ n_3 - 0.3785\ \alpha_{47}\ n_7$$

$$- 0.7394\ \alpha_{57}\ n_5 - 0.7836\ \alpha_{67}\ n_6 - \sum_{j=7}^{10} \alpha_{7j}\ n_j$$

TABLE 3.1 (cont'd)

$n = 8$

$$S_{u,8} = 0.5264\ \alpha_{66} \frac{n_6^2}{2} + 0.0058\ \alpha_{17}\ n_1\ n_7 + 0.0472\ \alpha_{27}\ n_2\ n_7 + 0.1592\ \alpha_{37}\ n_3\ n_7$$

$$+ 0.3785\ \alpha_{47}\ n_4\ n_7 + 0.7394\ \alpha_{57}\ n_5\ n_7 + \alpha_{67}\ n_6\ n_7 + 0.1984\ \alpha_{77} \frac{n_7^2}{2}$$

$$S_{p,8} = -\ 0.0044\ \alpha_{81}\ n_1 - 0.0367\ \alpha_{82}\ n_2 - 0.1242\ \alpha_{83}\ n_3 - 0.2947\ \alpha_{84}\ n_4$$

$$- 0.5758\ \alpha_{85}\ n_5 - 0.9951\ \alpha_{86}\ n_6 - \sum_{j=7}^{10} \alpha_{7j}\ n_j$$

$n = 9$

$$S_{u,9} = 0.2164\ \alpha_{76}\ n_6\ n_7 + 0.8016\ \alpha_{77} \frac{n_7^2}{2} + 0.0044\ \alpha_{81}\ n_8\ n_1 + 0.0367\ \alpha_{82}\ n_8\ n_2$$

$$+ 0.1242\ \alpha_{83}\ n_8\ n_3 + 0.2947\ \alpha_{84}\ n_8\ n_4 + 0.5758\ \alpha_{85}\ n_8\ n_5$$

$$+ 0.9951\ \alpha_{86}\ n_8\ n_6 + 0.5252\ \alpha_{87}\ n_8\ n_7$$

$$S_{p,9} = -\ 0.0035\ \alpha_{91}\ n_1 - 0.0293\ \alpha_{92}\ n_2 - 0.0994\ \alpha_{93}\ n_3 - 0.2359\ \alpha_{94}\ n_4$$

$$- 0.4610\ \alpha_{95}\ n_5 - 0.17967\ \alpha_{96}\ n_6 - \sum_{j=7}^{10} \alpha_{9j}\ n_j$$

$n = 10$

$$S_{u,10} = 0.4647\ \alpha_{87}\ n_8\ n_7 + 0.9278\ \alpha_{88} \frac{n_8^2}{2} + 0.0035\ \alpha_{91}\ n_9\ n_1$$

$$+ 0.0293\ \alpha_{92}\ n_9\ n_2 + 0.0994\ \alpha_{93}\ n_9\ n_3 + 0.2359\ \alpha_{94}\ n_9\ n_4$$

$$+ 0.4610\ \alpha_{95}\ n_9\ n_5 + 0.7967\ \alpha_{96}\ n_9\ n_6 + 0.7828\ \alpha_{97}\ n_9\ n_7$$

$$+ 0.2722\ \alpha_{98}\ n_9\ n_8$$

$$S_{p,10} = -\ 0.0027 \alpha_{10,1}\ n_1 - 0.0239\ \alpha_{10,2}\ n_2 - 0.0813\ \alpha_{10,3}\ n_3$$

$$- 0.1931\ \alpha_{10,4}\ n_4 - 0.3773\ \alpha_{10,5}\ n_5 - \sum_{j=6}^{10} \alpha_{10,j}\ n_j$$

3.6 Boundary Conditions for Particle Coagulation Equation

Referring to Fig. 3.1 once more, the boundary conditions for the particle coagulation equation are written as follows:

1) at $x=0$ and $0<y<y_1$, $y_2<y<y_3$, $y_4<y<y_5$ (at free surface)

$$\frac{\partial C_i}{\partial y}=0 \qquad (i=1,10) \qquad (3.6.1)$$

2) at $x=0$ and $y_1<y<y_2$, $y_3<y<y_4$ (at the up- and down leg)

$$C_i(\text{up-leg})=C_i(\text{down-leg}) \qquad (i=1,10) \qquad (3.6.2)$$

3) at $y=0$ or $y=y_5$ and $0<x<x_s$ (at the wall)

By using the mass transfer coefficient expression of Friedlander, the particle flux, q, from the fluid to the wall can be expressed as;

$$\frac{q}{V_p(C_N-C_p)}=\frac{\frac{f}{2}}{1+\sqrt{\frac{f}{2}}\left(\frac{1525}{S^{+2}}-50.6\right)}=\frac{\tau_w/\rho V_p^2}{1+\sqrt{\frac{\tau_w}{\rho V_p^2}}\left(\frac{1525}{S^{+2}}-50.6\right)} \qquad (3.6.3)$$

C_n; the particle density at the mode N

C_p; the particle density at the wall (=0)

f; the friction coefficient

S^+; non dimensional stopping length (equ. 2.6.14)

Tw; the shear stress on the wall

Chapter 4 Numerical Technique in Computation

In this chapter we shall present an outline of the numerical technique used for solving the differential equations developed in the preceding chapter.

4.1 Derivation of Finite-Difference Equations

In this section the reduction of finite-difference equations both for fluid flow and particle coagulation is discussed. The finite difference equations can be obtained by discretizing the general elliptic partial differential equations.

4.1.1 Derivation of the Finite-Difference Equation

The derivation of the finite-difference equation for a general elliptic, partial differential equations is summarized.

The general two dimensional elliptic differential equation (Steady State) has the following form

$$\underbrace{\frac{\partial}{\partial x}(\rho u\phi)+\frac{\partial}{\partial y}(\rho v\phi)}_{\text{convective term}} - \underbrace{\frac{\partial}{\partial x}\left(\Gamma_\phi\frac{\partial\phi}{\partial x}\right)-\frac{\partial}{\partial y}\left(\Gamma_\phi\frac{\partial\phi}{\partial y}\right)}_{\text{diffusive term}} = \underbrace{S_\phi}_{\text{source term}} \qquad (4.1.1)$$

This partial differential equation can be written as follows:

$$\frac{\partial\phi_1}{\partial x}+\frac{\partial\phi_2}{\partial y}=S_\phi \qquad (4.1.2)$$

where

$$\phi_1=(\rho u\phi)-\Gamma_\phi\frac{\partial\phi}{\partial x}$$

$$\phi_2=(\rho v\phi)-\Gamma_\phi\frac{\partial\phi}{\partial y}$$

Usually in a convective flow the diffusion term is negligible, while for a quiescent liquid the convective term is small in comparison to the diffusion term. The "central-difference scheme" leads to numerical instabilities when applied to strongly convective flows. In order to compensate for this, several algorithms have been suggested by Patankar [46]. These are 1) the upwind scheme, 2) the exponential scheme, 3) the Hybrid scheme, and 4) the power-law scheme. Here we shall consider a steady one-dimensional convection and diffusion equation with no source term:

$$\rho u \phi - \Gamma_\phi \frac{\partial \phi}{\partial x} = 0 \qquad (4.1.3)$$

This equation can be solved exactly when Γ_ϕ is a constant and with the following boundary conditions:

at $\quad x = 0 \quad \phi = \phi_0$

at $\quad x = L \quad \phi = \phi_L$

The solution is

$$\frac{\phi - \phi_0}{\phi_L - \phi_0} = \frac{\exp(P_e x/L) - 1}{\exp(P_e) - 1} \qquad (4.1.4)$$

where P_e is a Peclet number defined by:

$$P_e = \frac{\rho u L}{\Gamma_\phi} \qquad (4.1.5)$$

The Peclet number is the ratio of the strength of convection to diffusion. The charactristic of equation (4.1.4) is shown in Fig. 4.1. When P_e is very large, the value of ϕ in the domain is influenced by the upstream value of ϕ. Fig. 4.2 shows part of the orthognal grid with a typical node P and the surrounding nodes E, W, N and S. The exact solution of the one dimensional convection diffusion equation may be written as a finite-difference equation as follows:

$$F_e \left(\phi_P - \frac{\phi_P - \phi_E}{\exp(P_e) - 1} \right) - F_w \left(\phi_W + \frac{\phi_W - \phi_P}{\exp(P_w) - 1} \right) = 0 \qquad (4.1.6)$$

This finite-difference form can be transformed into a standard form:

$$a_P \phi_P = a_E \phi_E + a_W \phi_W \qquad (4.1.7)$$

where

$$a_E = \frac{F_e}{\exp(F_e/D_e) - 1} \qquad (4.1.8)$$

$$a_W = \frac{F_w \exp(F_w/D_w)}{\exp(F_w/D_w) - 1} \qquad (4.1.9)$$

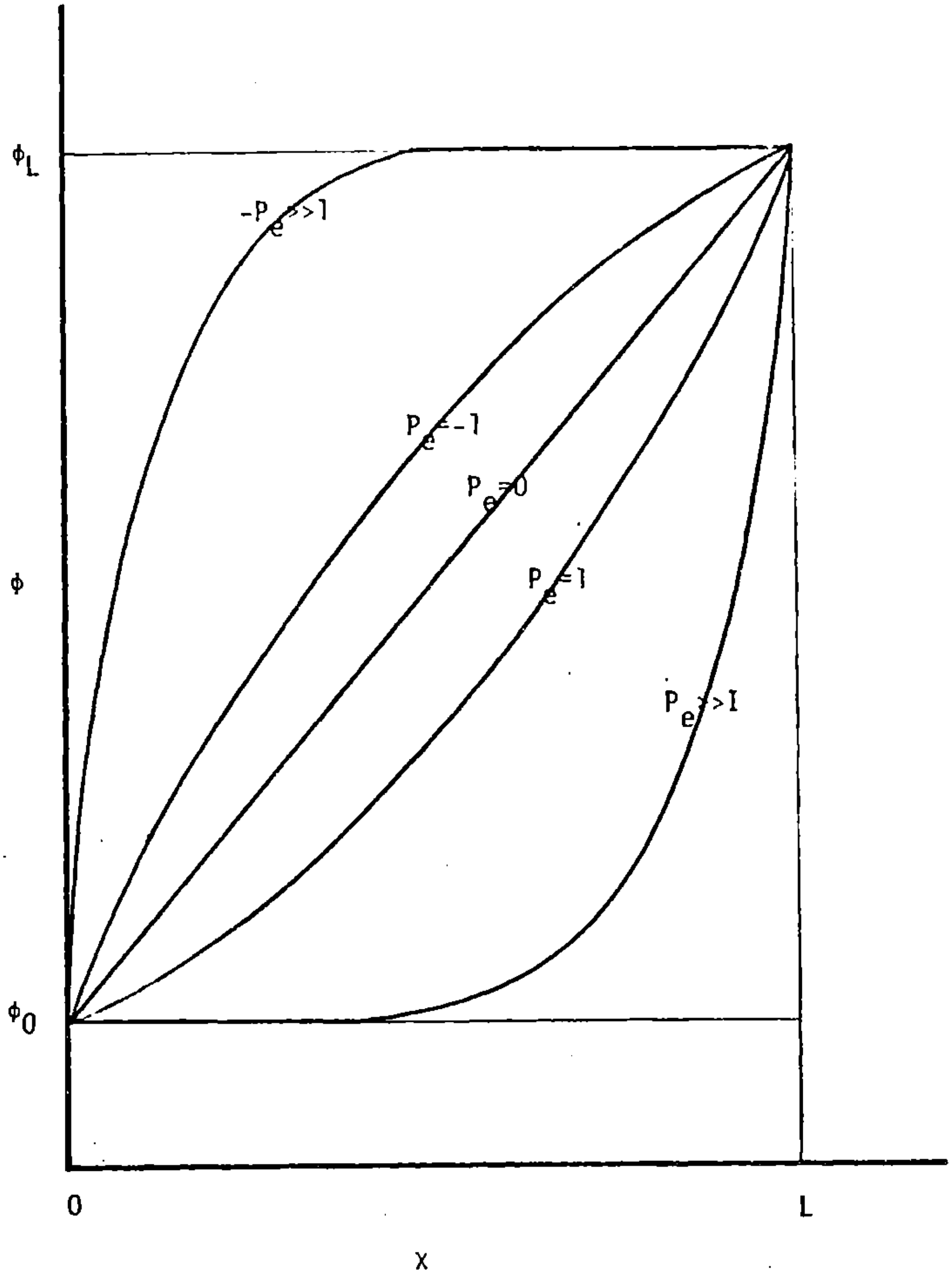


Fig. 4.1 Exact solution for the one dimensional convection-diffusion problem

and

$$F = \rho u \qquad D = \Gamma_\phi / \delta x$$

This is called the exponential scheme. Although this scheme is theoretically exact, it requires a large amount of computation time, and is therefore not practicable. The simplest approximation of the exact finite-difference scheme is the so called "upwind scheme". When F_e (and also F_w) is larger than zero

$$a_E = \frac{F_E}{(1+F_E/D_E)-1} = D_E \qquad (4.1.10)$$

$$a_W = \frac{F_W(1+F_W/D_W)}{(1+F_W/D_W)-1} = D_W + F_W \qquad (4.1.11)$$

On the other hand, when F_e (and F_w) is smaller than zero

$$a_E = \frac{F_E \exp(-F_E/D_E)}{1-\exp(-F_E/D_E)} = D_e - F_e \qquad (4.1.12)$$

$$a_W = D_W \qquad (4.1.13)$$

Equations (4.1.10) ∿ (4.1.13) can be written in a more correct form as:

$$\begin{aligned} a_e &= D_e + \llbracket -F_e, 0 \rrbracket \\ a_w &= D_w + \llbracket F_w, 0 \rrbracket \qquad (4.1.14) \\ a_p &= a_e + a_w + (F_e - F_w) \end{aligned}$$

where $\llbracket \quad \rrbracket$ denotes the largest of the arguments contained within it.

A more precise approximation of the exact solution was developed by Spalding. From (4.1.12) it follows that

$$\frac{a_e}{D_e} = \frac{P_e}{\exp(P_e)-1} \qquad (4.1.15)$$

The variation of A_e/D_e with Peclet number is shown in Fig. 4.1. The hybrid scheme consists of three parts.

$$\text{for} \quad P_e < -2 \qquad \frac{a_e}{D_e} = -P_e \qquad (4.1.16)$$

$$\text{for} \quad -2 \le P_e \le 2 \qquad \frac{a_e}{D_e} = 1 - \frac{P_e}{2}$$

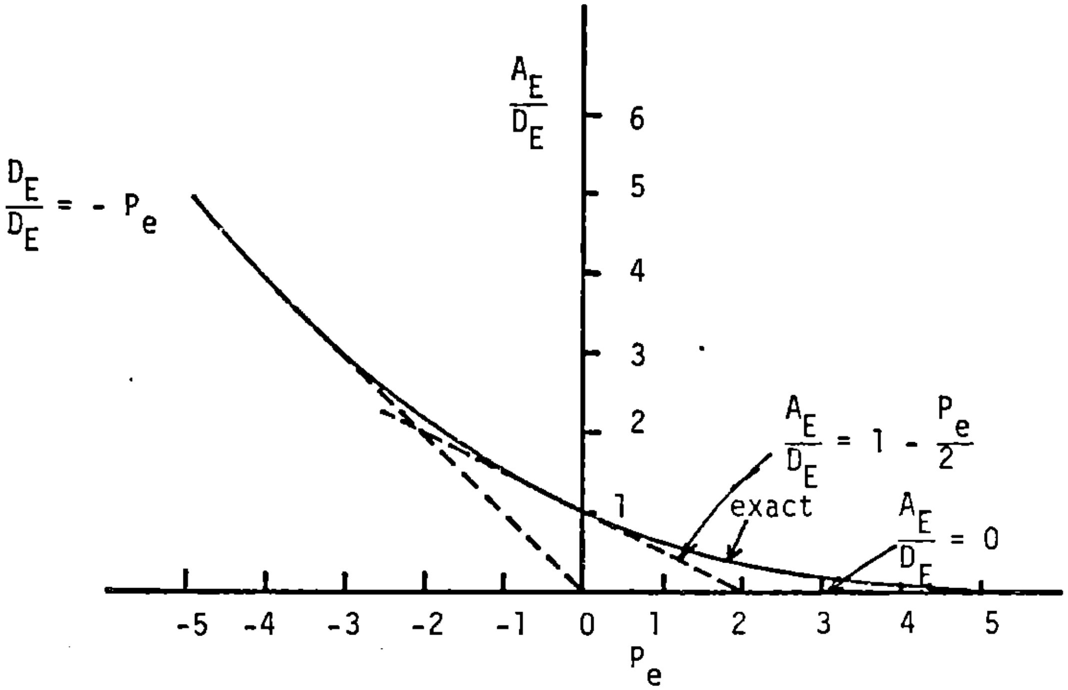


Fig. 4.2 Variation of the coefficient A_E with Peclet number

for $P_e > 2$ $\qquad \frac{a_e}{D_e} = 0$

These three equations can be expressed in a more convenient form as

$$
\begin{aligned}
a_e &= [\![-F_e ,\ D_e - \frac{F_e}{2}, 0]\!] \\
a_w &= [\![F_w ,\ D_w + \frac{F_w}{2}, 0]\!] \qquad (4.1.17) \\
a_p &= a_e + a_w + (F_e - F_w)
\end{aligned}
$$

We have discussed several schemes for the general one-dimensional elliptic partial differential equation. Similarly, the two-dimensional descretization equations can be written as

$$a_p \phi_p = a_e \phi_e + a_w \phi_w + a_n \phi_n + a_s \phi_s + b \qquad (4.1.18)$$

where

$$
\begin{aligned}
a_e &= D_e A(|P_e|) + [\![-F_e , 0]\!] \\
a_w &= D_w A(|P_e|) + [\![F_w , 0]\!] \\
a_n &= D_n A(|P_e|) + [\![-F_n , 0]\!] \qquad (4.1.19) \\
a_s &= D_s A(|P_e|) + [\![F_s , 0]\!] \\
b &= S_c \Delta x \Delta y \\
a_p &= a_e + a_w + a_n + a_s - S_p \Delta x \Delta y
\end{aligned}
$$

In this expression, A $(|P_e|)$ depends the scheme used and is shown in Table 4.1. F_e, F_w, F_n, and F_s are the mass flow rates through the surfaces of the control volume.

$$
\begin{aligned}
F_e &= (\rho u)_e \Delta y \\
F_w &= (\rho u)_w \Delta y \qquad (4.1.20) \\
F_n &= (\rho v)_n \Delta x \\
F_s &= (\rho v)_s \Delta x
\end{aligned}
$$

D_e, D_w, D_n, and D_s are the diffusion conductances through the faces and are defined as follows:

$$
\begin{aligned}
D_e &= \frac{\Gamma_e \Delta y}{(\delta x)_e} \\
D_w &= \frac{\Gamma_w \Delta y}{(\delta x)_w} \\
D_n &= \frac{\Gamma_n \Delta x}{(\delta y)_n} \qquad (4.1.21) \\
D_s &= \frac{\Gamma_s \Delta x}{(\delta y)_s}
\end{aligned}
$$

Table 4.1 The function $A(|P|)$ for different schemes (by Patankar)

Scheme	Formulation for $A(\|P\|)$
Central difference	$1 - 0.5\,\|P\|$
Upwind	1
Hybrid	$[0,\ 1 - 0.51\,\|P\|]$
Power law	$[0,\ (1 - 0.1\,\|P\|)^5]$
Exponential	$\|P\|/[\exp(\|P\|) - 1]$

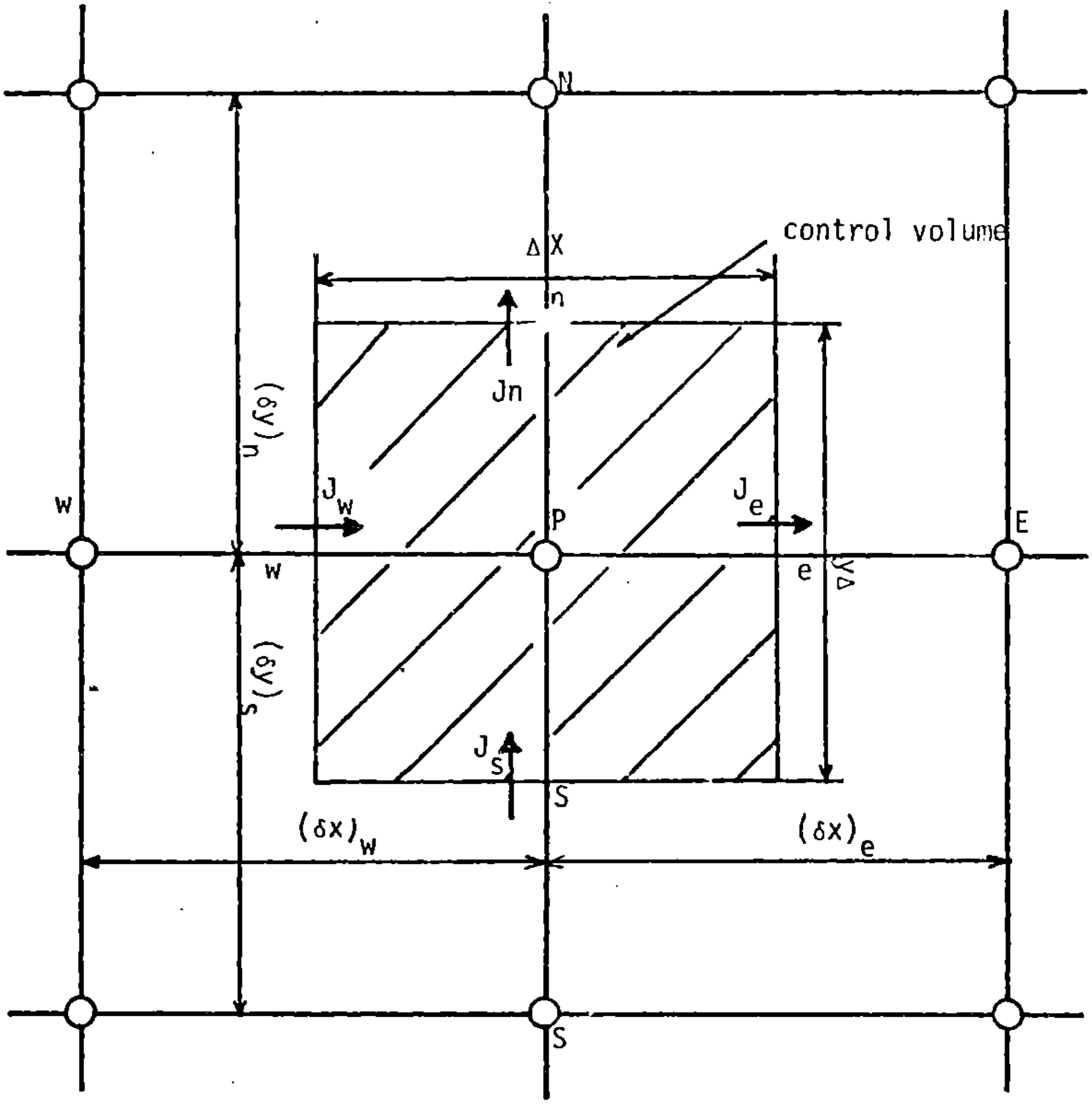


Fig. 4.2 Portion of the finite-difference grid

4.1.2 Finite Difference Representation of the Transient Two-Dimensional Elliptic Equation

$$\frac{\partial}{\partial t}(\rho\phi)+\frac{\partial}{\partial x}(\rho u\phi)+\frac{\partial}{\partial y}(\rho v\phi)-\frac{\partial}{\partial x}\left(\Gamma_\phi\frac{\partial\phi}{\partial x}\right)-\frac{\partial}{\partial y}\left(\Gamma_\phi\frac{\partial\phi}{\partial y}\right)=S_\phi \qquad (4.1.22)$$

Generally we can deduce the finite-difference form for the transient two-dimensional elliptic partial differential equation by using a weighting factor λ. Equation (4.1.18) can be replaced by the finite-difference expression

$$\frac{\partial(\rho\phi)}{\partial t}+a_p\phi_p=\sum_{i=n,s,w\ s}a_i\phi_i+b \qquad (4.1.23)$$

where the subscript p denote the central point and the subscript i denotes its neighbors. In order to deduce the finite-difference expression for the transient partial differential equation, $\partial(\rho\phi)/\partial t$ is replaced by $\rho(\phi_p^{k+1}-\phi_p^k)/\Delta t$ and ϕ_p and ϕ_n are expressed as weighted mean concentrations as follows;

$$\begin{aligned}\rho(\phi_p^{k+1}-\phi_p^k)\ \Delta x\Delta y/\Delta t &+ \{(1-\lambda)a_p^k\phi_p^k+\lambda a_p^{k+1}\phi_p^{k+1}\}\\ &=\{(1-\lambda)\sum a_i^k\phi_i^k+\lambda a_i^{k+1}\phi_i^{k+1}\}\\ &\quad+\{(1-\lambda)b^k+\lambda b^{k+1}\}\end{aligned} \qquad (4.1.24)$$

where the superscript k or k+1 denotes the number of the time step. In the present computation A_n, A_s, A_w, and A_e are independent of the time step, and the super script k or k+1 can be dropped, while the terms A_p and b have different values for each time step. Then

$$\begin{aligned}a_p^k&=a_e+a_w+a_n+a_s-S_p^k\Delta x\Delta y\\ b^k&=S_c^k\Delta x\Delta y\end{aligned} \qquad (4.1.25)$$

Rearranging the equation (4.1.24), we obtain the final form for the finite-difference computation.

$$\begin{aligned}\left\{\frac{\rho\Delta x\Delta y}{\Delta t}+\lambda a_p^{k+1}\right\}\phi_p^{k+1}\\ &=\lambda\sum a_i\phi_i^{k+1}+\lambda b^{k+1}\\ &\quad+\left[\frac{\rho\Delta x\Delta y}{\Delta t}\phi_p^k+(1-\lambda)a_p^k\phi_p^k+(1-\lambda)\sum a_i\phi_i^k+(1-\lambda)b^k\right]\end{aligned}$$

(4.1.25)

If λ = 1, equ. (4.1.25) becomes the implicit scheme. If $\lambda = \frac{1}{2}$, we obtain the Crank-Nicolson formula. On the other hand, if λ = 0, the explicit formula is obtained. In present calculations, the fully implicit scheme is employed

$$\left\{\frac{\rho\Delta x\Delta y}{\Delta t}+a_p^{k+1}\right\}\phi_p^{k+1} = \sum_i a_i\phi_i^{k+1}+b^{k+1}+\frac{\rho\Delta x\Delta y}{\Delta t}\phi_p^{k} \qquad (4.1.26)$$

and the final discretization equation can be written as

$$a_p\phi_p^{k+1} = a_e\phi_e^{k+1}+a_w\phi_w^{k+1}+a_n\phi_n^{k+1}+a_s\phi_s^{k+1}+b \qquad (4.1.27)$$

where A_E, A_W, A_n, and A_s have the same form as obtained in equ. (4.1.17) and

$$\begin{aligned} a_p^0 &= \frac{\rho\Delta x\Delta y}{\Delta t} \\ b &= S_c\Delta x\Delta y+a_p^0\phi_p^k \\ a_p &= a_e+a_w+a_n+a_s+a_p^0-S_p\Delta x\Delta y \end{aligned} \qquad (4.1.28)$$

4.2 Solution Procedure

4.2.1 Tridiagonal Matrix Algorithm

The solution of the discretization equation formulated in the preceeding chapter is obtained by the standard Gassian-elimination method. Because of its simplicity, this argorithm is very useful.

The general form of the equations to be solved can be expressed as

$$a_i\phi_i = b_i\phi_{i+1} + c_i\phi_{i-1} + d_i \qquad (4.2.1)$$

where i is the number of thr grid point and points 1 and n denote the boundary point. In any boundary condition, T_n or $(\frac{\partial T}{\partial x})_n$ is given, therefore $C_1 = 0$ and $b_n = 0$ could be set. This enables us to begin a "back-substitution" process in which ϕ_{n-1} is determined by ϕ_n, and ϕ_{n-2} from ϕ_{n-1}. The following form is obtained by elimination;

$$\phi_i = P_i\phi_{i+1} + Q_i \qquad (4.2.2)$$

and the coefficients P_i and Q_i are given by

$$P_i = \frac{b_i}{a_i - c_i P_{i-1}}$$
$$Q_i = \frac{d_i + c_i Q_{i-1}}{a_i - c_i P_{i-1}} \qquad (4.2.3)$$

The equation for i = 1 is given as

$$P_1 = \frac{b_i}{a_i} \qquad Q_1 = \frac{d_1}{a_1} \qquad (4.2.4)$$

For the time-dependent problem, more calculation is required, but this algorithm is also applicable. This procedure is performed in the program SOLVE. In effect, when solving nonlinear partial differential equations the coefficients cannot be determined explicitly, so that several iterations are required.

4.2.2 Pressure Correction Equation

The aim of the pressure correction equation is to modify the velocity components u and v so as to conserve the mass continuity in a control volume.

After the momentum equation is solved, the pressure correction equation, derived from the continuity equation, is applied

$$a_p P'_p = a_w P'_w + a_e P'_e + a_n P'_n + a_s P'_s + b \qquad (4.2.5)$$

where

$$a_e = \rho_e d_e \Delta y$$
$$a_w = \rho_w d_w \Delta y$$
$$a_n = \rho_n d_n \Delta x$$
$$a_s = \rho_s d_s \Delta x$$
$$a_p = a_e + a_w + a_n + a_s$$
$$b = [(\rho u^*)_w - (\rho u^*)_e]\Delta y + [(\rho v^*)_s - (\rho v^*)_n]\Delta x$$

The correction to the velocity is made as follows:

$$u_e = u_e^* + d_e(P'_p - P'_e) \qquad (4.2.6)$$

The correction formula in other directions can be derived similarly.

4.3 Flow Sheet and Computer Program for Computation

4.3.1 Flow Field Calculation

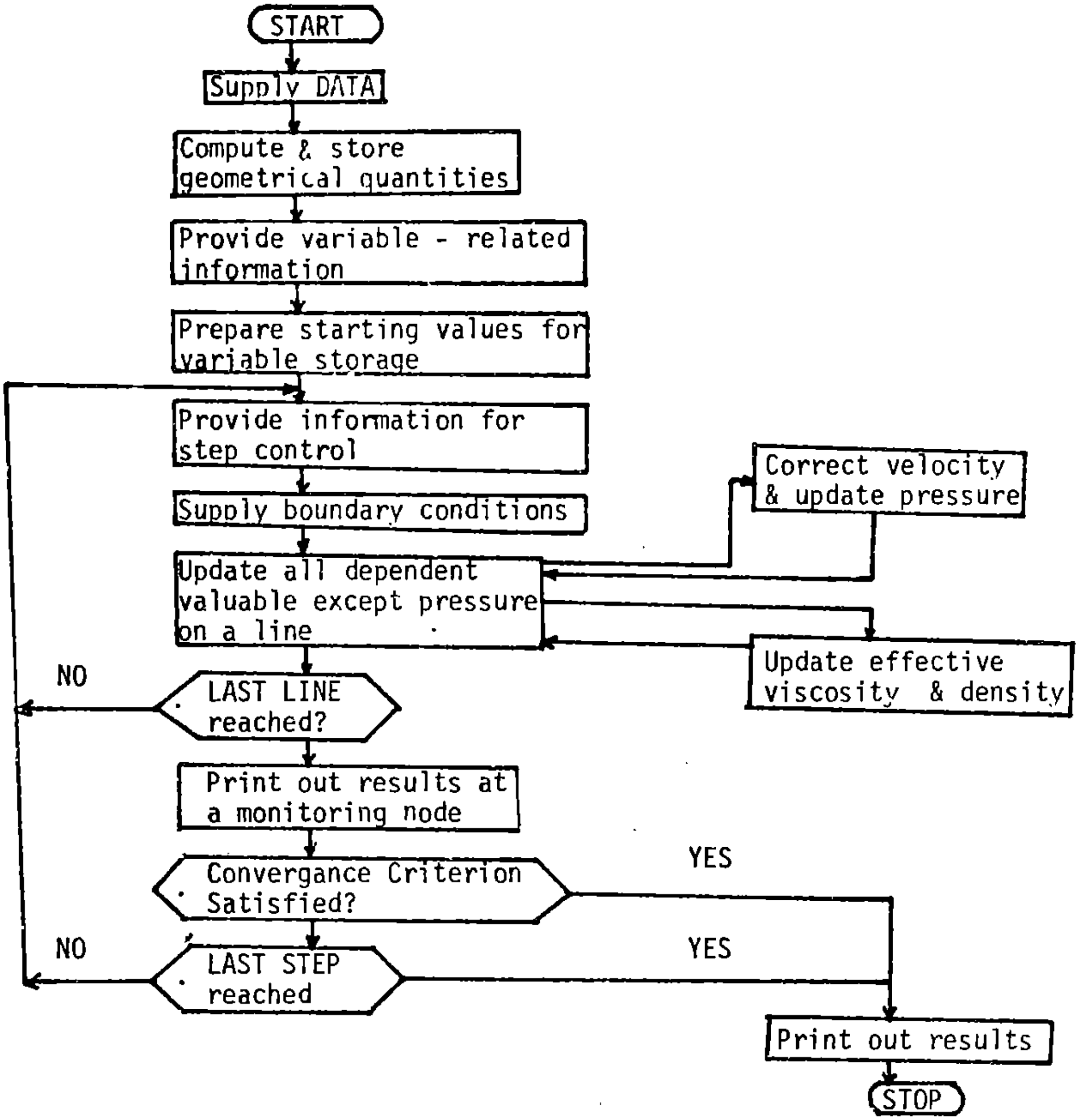
Fig. 4.3 shows a flow chart of the computation. In the present computation, the four dependent variables u, v, k and ε are calculated, and updated in that order. The effective viscosity μ_{eff} is an independent variable which is determined by k and ε. Along one X-line, all of the four dependent variables are updated using the Gausian-elimination algorithm. This is then repeated for the next X-line. In this way, a total of NX lines are updated. After each iteration is complete, the value of μ_{eff} for each grid point is calculated, and u and v are corrected so as to observe mass continuity. The calculated value of effective viscosity is used for the next calculation. This procedure is continued until the residue and the difference of values between successive iterations are less than a specified value.

The program was initially developed by Pun and Spalding for turbulent pipe flow. The program can be divided into several subroutines the tasks of which are listed on Table 4.2 The listing of the program is given in Appendix A.

4.3.2 Particle Coagulation Program

Fig. 4.4 shows a flow chart of the computation scheme. In the present work, particle sizes are divided into ten classes and transient partial differential equations are solved in each size group. A single interation is performed for each dependent variable along successive X-lines. For the calculation of the source terms, the field values computed at the previous sweep are employed. After covergence is obtained at each time step, the calculation for the next time step is performed until the final time step is reached. The structure of this program is shown in Fig. 4.5 The structure

Fig. 4.3 Flow chart of the computational scheme



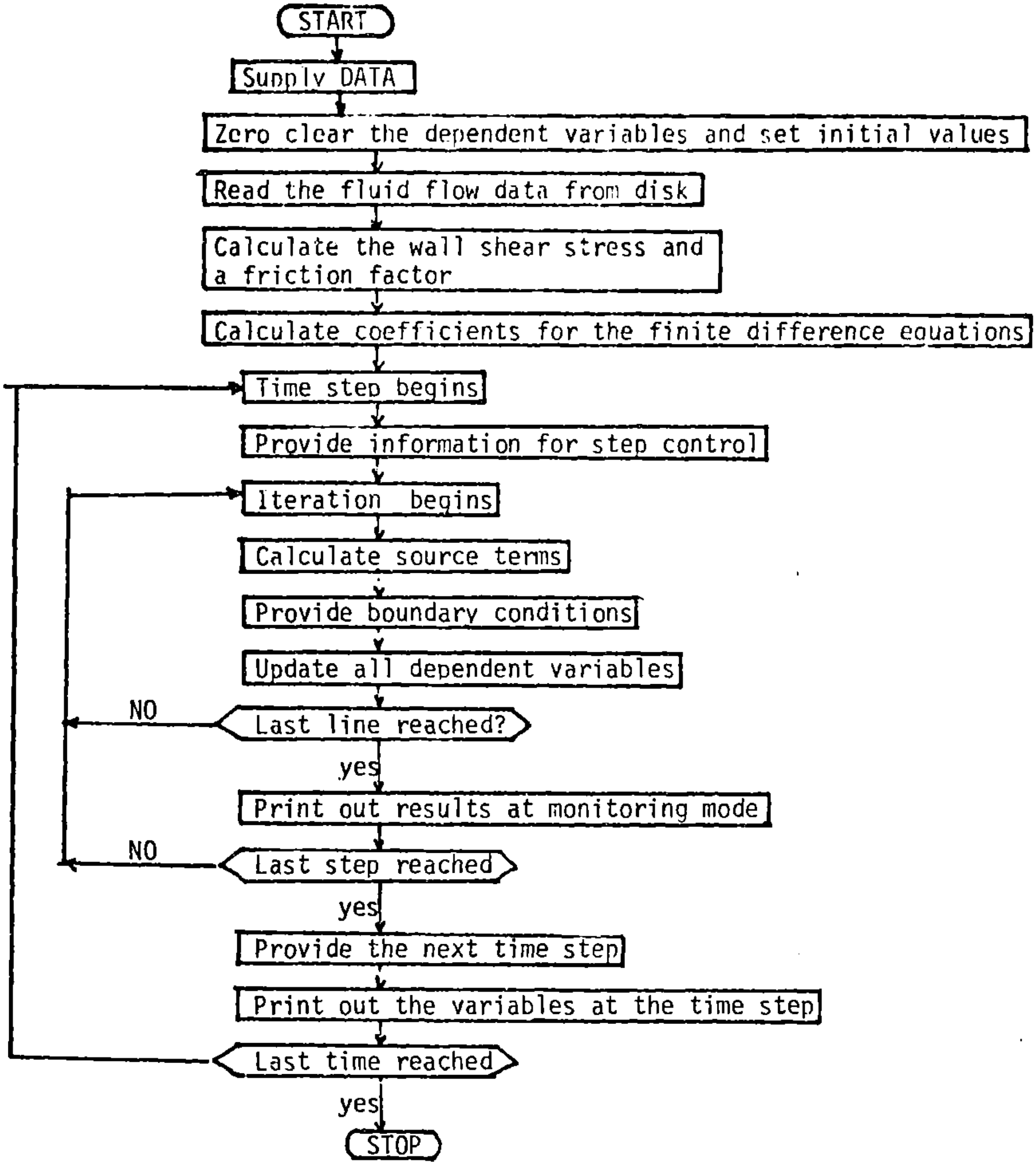


Fig. 4.4 Flow chart of the computational theme for particle coagulation

Table 4.2 Function of the Subroutines

Name:	Function:
MAIN	Starts the computations and controls the iteration procedure.
BLOCK DATA	Specifies numerical data and control indices for the problem.
OUTPUT	Organizes the bulk of the print-out results; divided into four parts by an entry statement.
OUTPH	Prints out headings like problem titles, size of the system, etc.
OUTPF	Prints out the field values of dependent variables.
OUTP1	Prints residual-source information and variable values at a monitoring mode.
OUTP2	Provides output of pipe flow characteristics
CONST	
CONST 2	Calculates quantities related to NX and NY.
CONST 3	Calculates all constants related to the variables.
CONST 5	Provides constants for starting preparations.
ADJUST	Performs various adjustments to the different variables in order to enhance the rate of convergence.
AVACON	Adjusts the mean pressure. This is not used in the present case.
CELCON	Applies the cell-wise continuity correction, through the use of pressure-correction values.
BOUND	Updates values on boundaries of the flow domain.
SOURCE	Supplies source terms Su and Sp not provided in subroutine COEFF.
MODIFY	Makes all modifications to boundary conditions.
GEOM	Evaluates all geometrical quantities related to the grid.
COEFF	Calculates all coefficients of the finite-difference equations.
CELPHI	Provides cell-wall densities and viscosities for u-, v- and other cells.
SOLVE	Solves the finite-difference equations by means of the tri-diagonal matrix algorithm.

Table 4.2 Function of the Subroutines (cont'd)

Name:	Function:
PRINT	Prints variable-values in the two-dimensional field.
TEST	Prints information for program testing; consists of seven sections: TEST 11, TEST 12, TEST 13, TEST 21, TEST 22, TEST 23 and TEST 31.

itself is very similar to the fluid flow program except for the transient feature. The listing of program is given in Appendix B.

4.4 Stability and Convergence

Two problems crucial to the successful solution of the coupled finite difference non linear equations are the stability and the rate of convergence. Instabilities are caused not only by the presence of round-off or other computation error, but also by large time steps. Stability analysis has been performed on several simple finite difference schemes. In general, however, it is not possible to extend this analysis to non linear coupled equations. As Patankar said in his book [47], there is no general guarantee that, for all non linearities and inter-linkages, we will obtain a convergent solution.

In order to avoid divergence in the iterative scheme, an underrelaxation technique is often employed. If ϕ_{old} is the value of the variable calculated in the last iteration and ϕ_{new} is the new value the use of a relaxation factor, α, defined by

$$\phi = \alpha\,\phi_{new} + (1-\alpha)\,\phi_{old} \qquad (4.4.1)$$

causes the dependent variables to respond more slowly to the cahnge in other variables. A diffusion coefficient Γ can also be under-relaxed to reduce the influence of other variables. Teh present value of Γ is calculated from

$$\Gamma = \alpha\,\Gamma_{new} + (1-\alpha)\,\Gamma_{old} \qquad (4.4.2)$$

The relaxation factor is required to be positive and less than 1. Other variables, for example the source term or the boundary value, may also be underrelaxed. The values of α for each case need not to be the same. Therefore, it is very difficult to determine the optimum combination of the relaxation parameters for each variable and coefficient.

Convergence is checked by two different criteria. One of these is the residual RS_p which is calculated as follows;

$$RS_p = \phi_p\left(\sum_i a_i S_p\right) - \left(\sum_i a_i \phi_i + S_u\right) \qquad (4.4.3)$$

where i = W, E, N, S. Just as before, the values of a variable on a line are updated and the algebraic seem of the residual sources on the line for the variable is calculated with the finite-difference coefficient available. The sum of the absolute value of the algebraic-source term on each line over the whole domain is required to be less than a prescribed small value, i.e.

$$\sum_i \Big| \sum_j (RS_{i,j}) \Big| < \varepsilon_1 \qquad (4.4.4)$$

where i and j express the lines over the whole domain and the nodes on a line respectively.

Another criterion is used in the present calculation. This alternative criterion has been used by some investigators [53].

$$\frac{\sum |\phi_{new} - \phi_{old}|}{\sum |\phi_{new}|} \le \varepsilon_2 \qquad (4.4.5)$$

where Σ means summation over all the interior nodes. In the present numerical calculation for fluid flow, equs. (4.4.4) and (4.4.5) are used. ε_1 was set to 0.001 and ε_2 to 0.005. In the calculation for particles coagulation, equ. (4.4.3) was used and ε_2 was set to 0.03.

Chapter 5 Computed Results and Discussion

The model developed in Chapter 3 was used to predict the fluid flow and particle coagulation process in the R-H vacuum degasser. The calculated results of the flow field in the ladle were used for the prediction of coagulation rate.

5.1 Fluid Flow Calculation

5.1.1 System, Physical Properties and Parameters

The system chosen for computation was the ladle of a 150 ton R-H degassing system. The ladle diameter, Xs, was 2.5m and its height, Ys, was 2.5m. The values of the physical properties used for the computation are listed in Table 5.1. The values used in this computation are common in the literature. The values for the empirical constants C_1, C_2, C_D, σ_k and σ_ε of the k-ε model are those recommended by Launder and Spalding. This set of numerical values is adequate for many applications and a more extensive disscusions is provided by the same authors.

5.1.2 Computational Details

A 15 (X-direction) X 18 (Y-direction) finite difference grid as shown in Table 5.2. The nodes are spaces so as to be concentrated in the regions a wall or free surface. The relaxation factors and the direction of sweeps are shown in Table 5.3. The computation was carried out using the IBM370/168 digital computer at M.I.T. The compilation of the program required 25 sec. and a typical run required 180 sec.

5.1.3 Computed Results and Discussion

Fig. 5.1 represents the computed velocity field in the 150 ton ladle for an inlet velocity of 72cm/s. It is seen that there are two regions of local recirulation; one near the surface and one in the vinicinity of the left side wall. According to the calculation of Nakanishi, et al. [1] who

Table 5.1 Numerical value of parameters (fluid flow)

X_s	Height of a ladle	250 (cm)
Y_s	Diameter of a ladle	250 (cm)
R	Diameter of up- or down leg	35 (cm)
ρ	Density of molten steel	7.2 (g/cm^3)
μ	Viscosity of molten steel	0.06 (g/cm sec.)
C_1	Constant in k-ε model	1.44 (-)
C_2	Constant in k-ε model	1.92 (-)
C_D	Dissipation constant	0.09 (-)
σ_k	Effective Prantdl number for k	0.9 (-)
σ_ε	Effective Prantdl number for ε	1.0 (-)

Table 5.2 Ditails of the finite-difference grid

x (i)		y (i)		
x (1)	0	y (1)	0	
	5.0		6.25	
	25.0		21.25	
	45.0		26.25	
	65.0		53.75	} down-leg
	85.0		71.25	
	105.0		88.75	
	125.0		103.25	
	145.0		117.75	
x (10)	165.0	y (10)	132.25	
	185.0		146.75	
	205.0		161.25	
	225.0		178.75	} up-leg
	245.0		196.25	
x (15)	250.0		213.75	
			228.75	
			243.75	
		y (18)	250.0	

Table 5.3 Details of computation

NO of iteration	u	v	k	ε	ρ'	μ	Direction of sweep
1-100	0.3	0.6	0.5	0.5	0.6	0.5	single
100-720	0.3	0.6	0.7	0.7	0.6	0.5	single

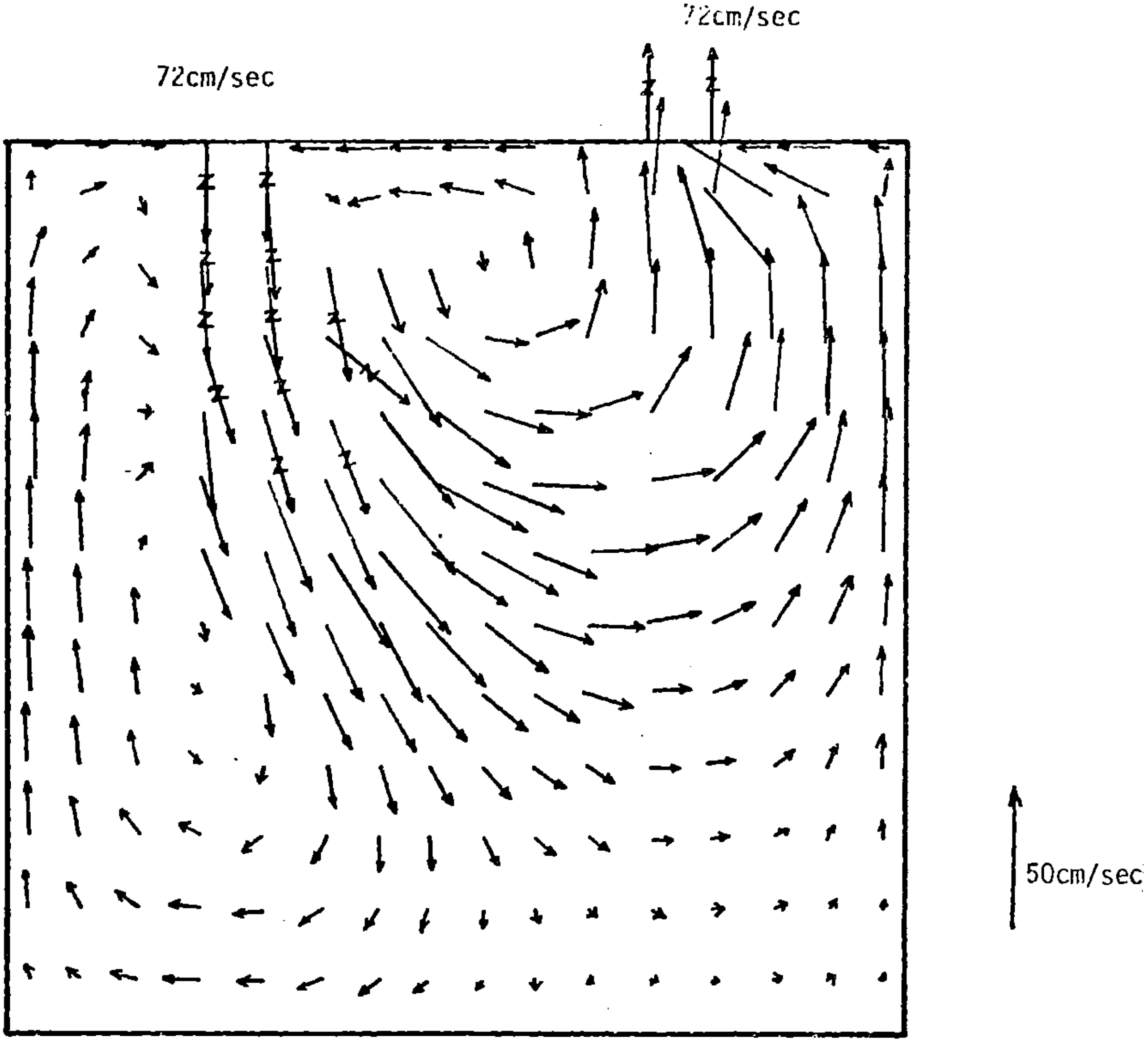


Fig. 5.1 Velocity field in the ladle of the R-H system (cm/sec).

used the vorticity-stream function program, there seem to be three local circulations. Since they assumed a free surface condition at the top of the ladle, there was no circulation between the two legs. Although a realistic boundary condition would be neither a solid surface condition nor a free surface condition (due to the existance of slag layer), it is apparent that there would be a local surface circulation when the solid surface condition weakened. The reason why the relatively large circulation occurs near the wall of down-leg side is not clear, but the high momentum of the flow in ments seems to cause some "choking effect", which results in recirculation. At the bottom of the ladle, the metal velocities are much smaller (minimum 1.0 cm/s) but still non zero.

The computed spatial distribution of the turbulent kinetic energy, k, and the turbulent dissipation energy, ϵ, are shown in Fig. 5.2 and Fig. 5.3, respectively. The two profiles are very similar, but the decrease in the dissipation energy towards the wall is much faster than that in the kinetic energy. The maximum value of both kinetic turbulent energy and the dissipation energy appear just under the down-leg. On the contrary, Nakanishi's calculation showed that the maximum value appears under the up-leg. This seems to come from a difference of the boundary conditions for the up-leg. In the present calculation, we used the same boundary conditions both for the discharge and the suction area but Nakanishi used the zero-gradient boundary condition which is valid only for the free-surface.

Fig. 5.4 shows the distribution of the eddy diffusivity. The eddy diffusivity also has the maximum value under the down-leg (72 cm/sec). Fig. 5.5 shows the distribution of the ratio of the effective viscosity to the molecular viscosity. The maximum value of this ratio is about 8000.

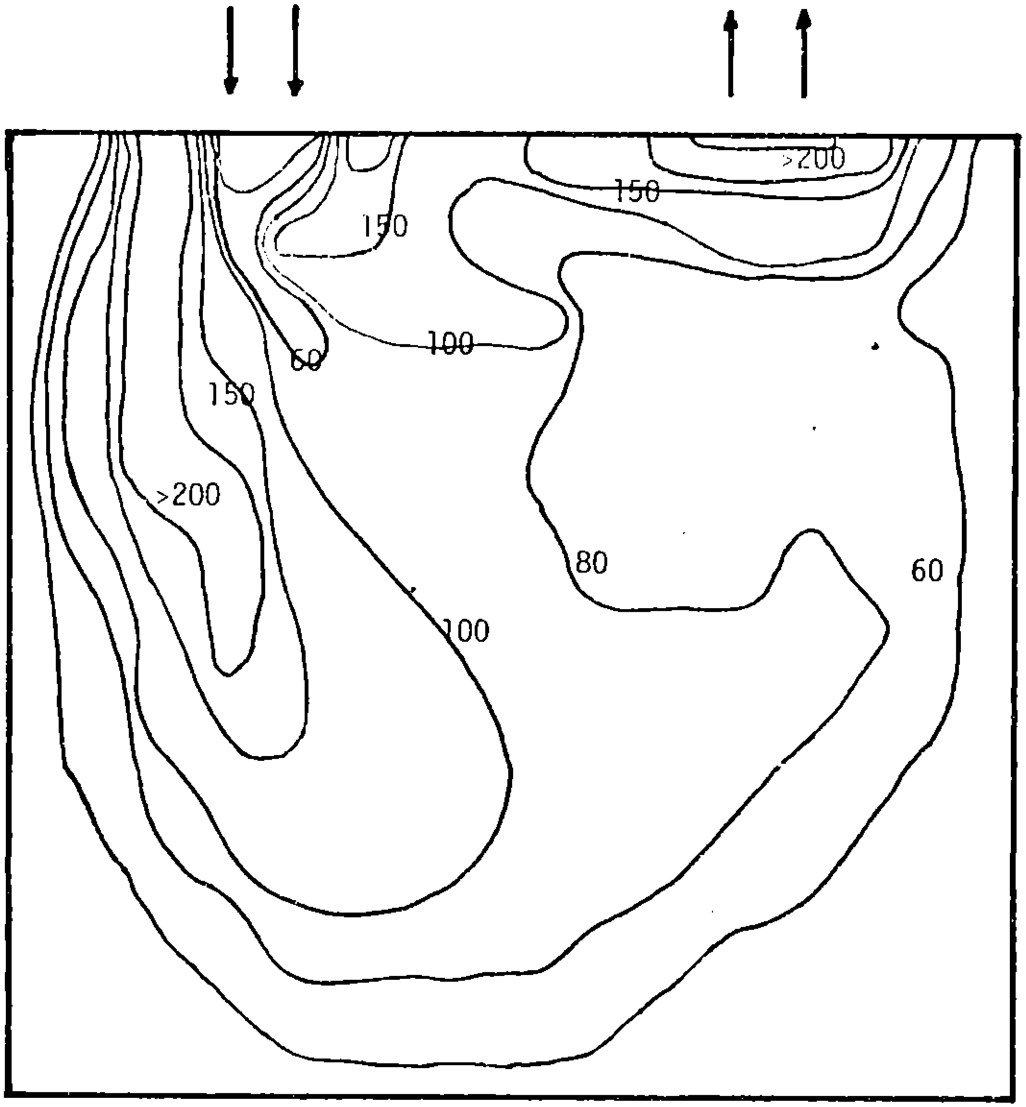


Fig. 5.2 Distribution of the kinetic energy k (cm^2/sec^2).

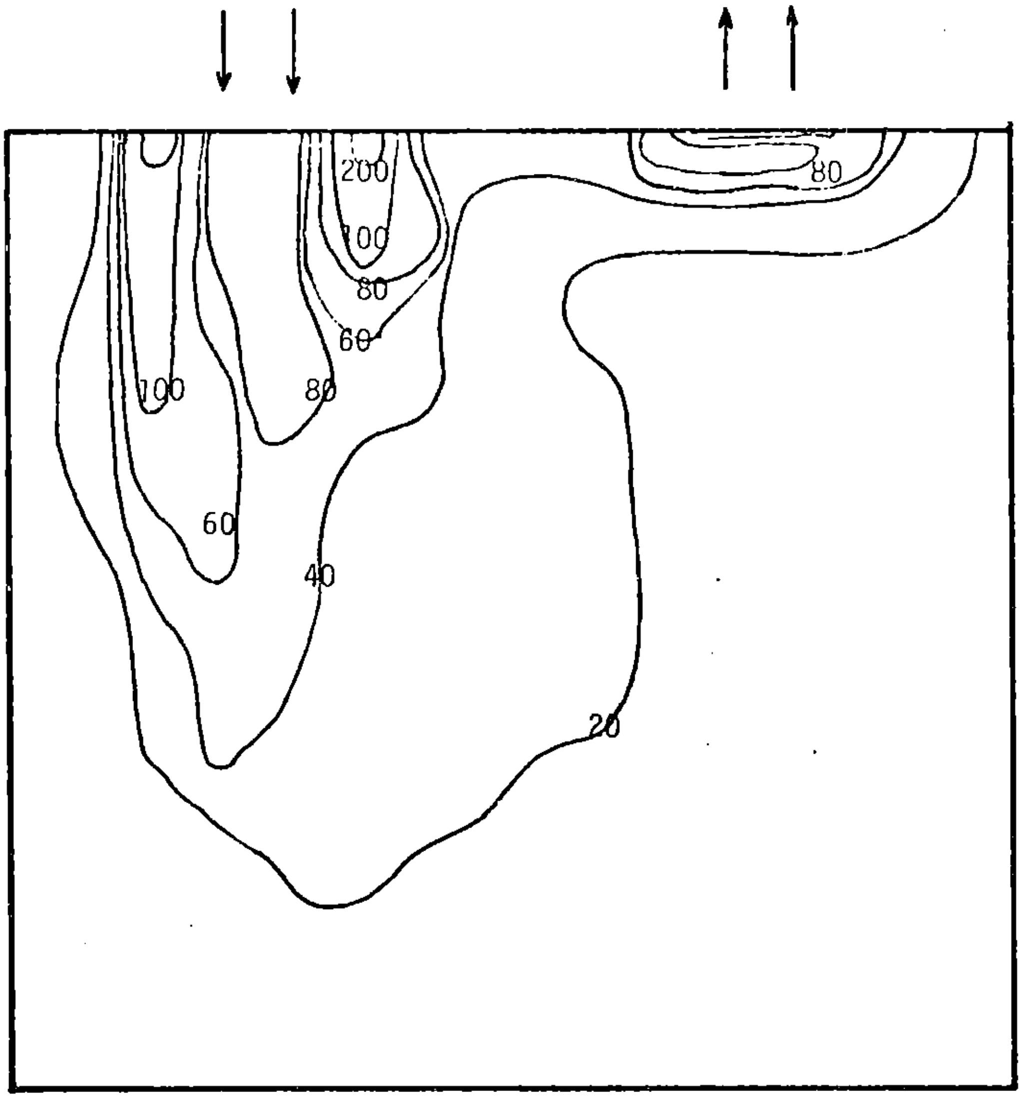


Fig. 5.3 Distribution of the turbulent dissipation energy ϵ (cm^2/sec^3).

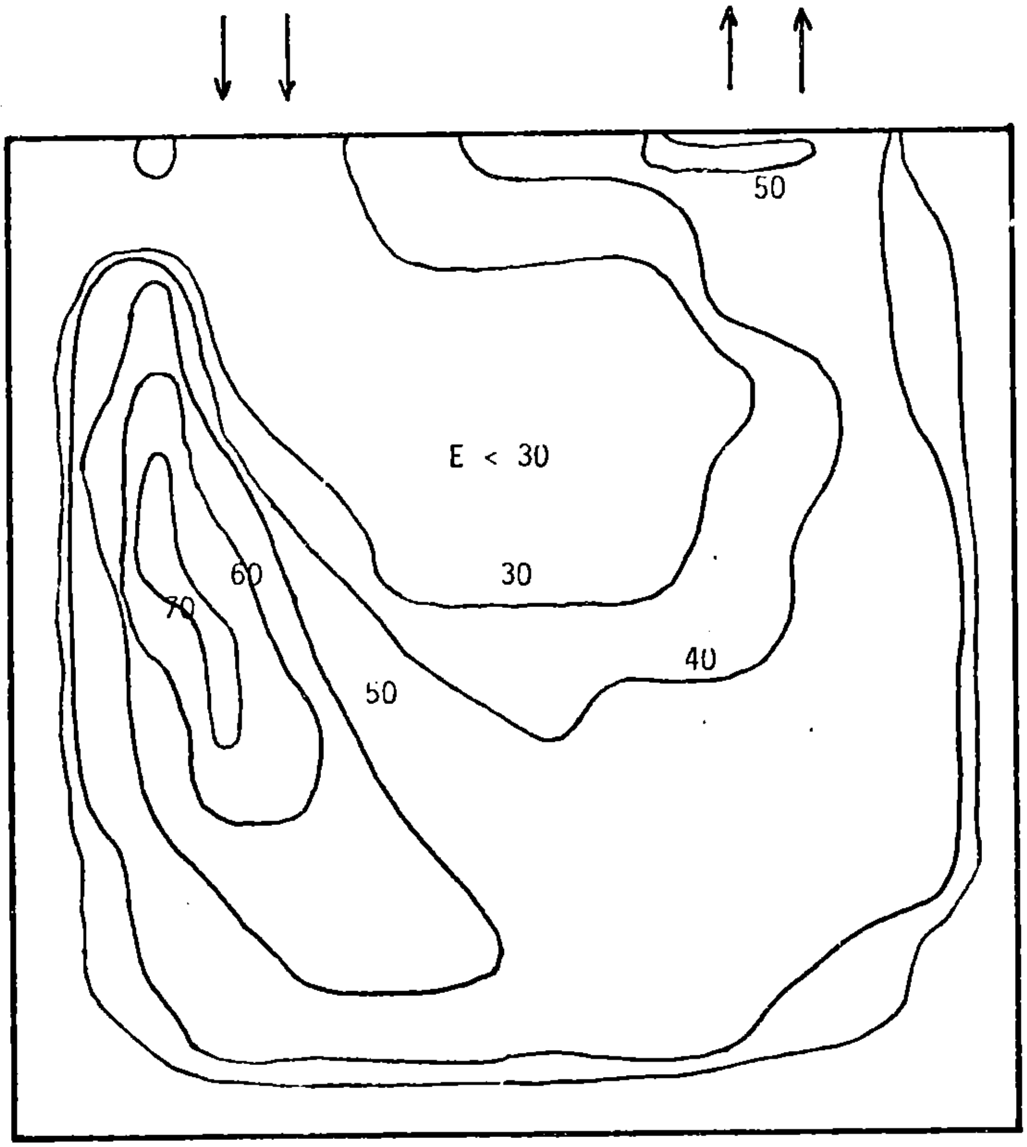


Fig. 5.4 Distribution of the eddy diffusivity E (cm^2/sec).

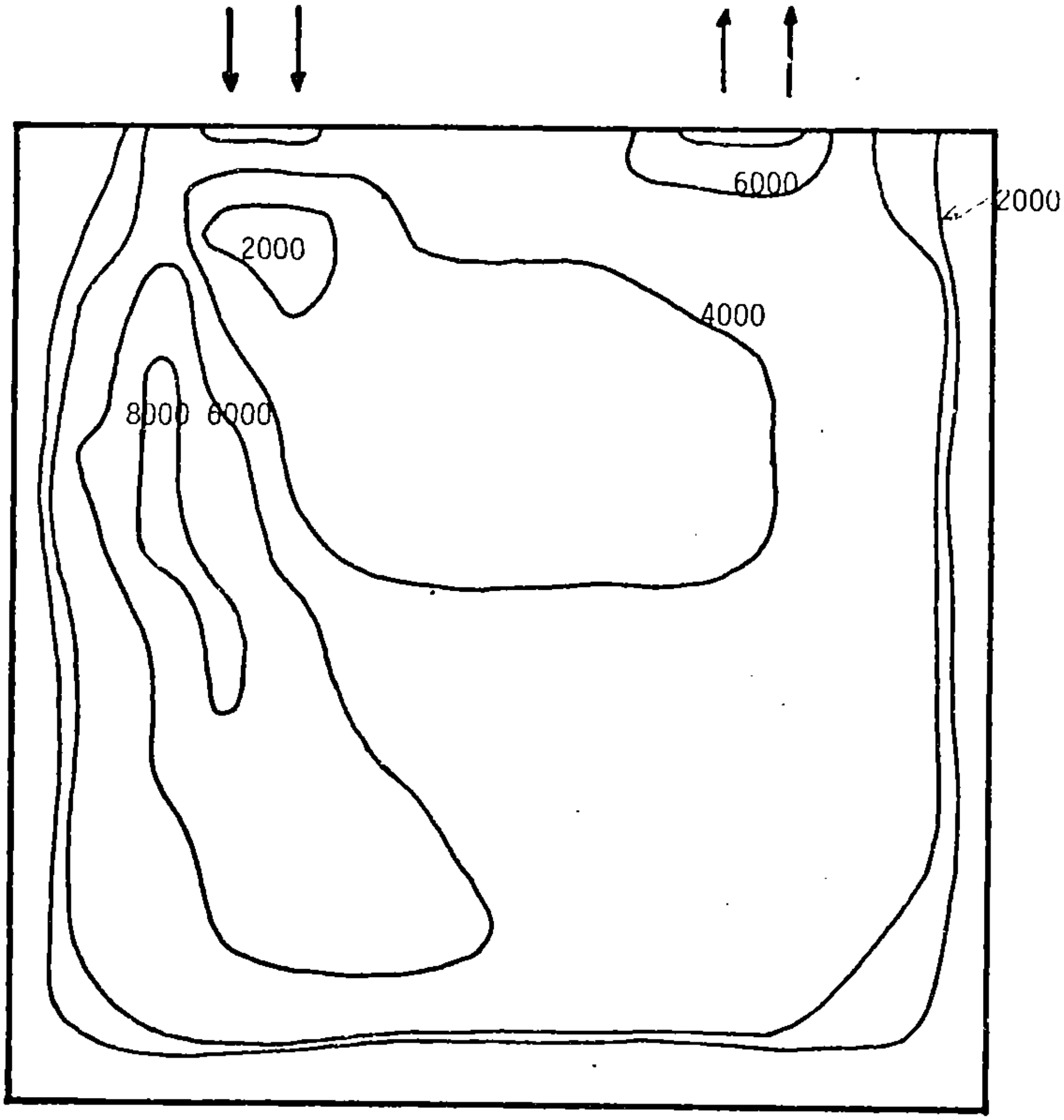


Fig. 5.5 Distribution of the ratio (μeff/μ)

5.2 Particle Coalescence Calculation

5.2.1 Data used for the Calculation

In the present calculation, as mentioned in the previous chapter, the fluid flow data computed for the case of steady condition were used for the transient particle transport equation. All of the data computed in the F array, which is equivalent to nine dependent valuables were stored on a disk after convergence was reached.

The initial particle size distribution was taken from the available published and unpublished data. The initial distrubution of particle size may depend on the process and the pretreatment method, but the disbrubution is assumed so as to represent the real situation as well as possible.

5.2.2 Computational Details

The finite difference grid used for the particle coagulation model was the same as that used for the fluid flow calculation. The important information of the details of the computation is listed in Table 5.4 The compilation time and the execution time of the program were about 25 sec. and 860 sec., respectively. In the present calculation the wall function for the particle coagulation was not calculated

5.2.3 Computational Results and Discussions

Fig. 5.7 - Fig 5.11 represent the computed particle density distribution at nodes 50, 81, 112, 128, 176, 224. These grid points are chosen so as to monitor the dependence on the dissipation energy, the velocities and the wall effect. The location of these grid points are shown in Fig. 5.6. Although the particle density distributions seem to be similar, some significant characteristics are found. At every grid point the larger particles increase in number at the initial stage (at 10 sec.), but soon begin to decrease, and at the time $t = 60$ sec. the number of particles of size $d = 20\mu m$ becomes almost the same as the initial value. Since it is assumed that all

Table 5.4 The detail of computation for particle coagulation

Time (sec.)	Time interval	Prantle Number $\sigma_{c,i}$	relaxation parameter $\alpha_{i,c}$	The number of iteration	sweep
0	10	1.0	1.0	5	single
10	10	1.0	1.0	5	"
20	20	1.0	1.0	5	"
40	20	1.0	1.0	5	"
60	30	1.0	1.0	5	"
90	30	1.0	1.0	5	"
120	60	1.0	1.0	5	"
180	60	1.0	1.0	5	"
240	60	1.0	1.0	5	"
300	100	1.0	1.0	5	"
400	100	1.0	1.0	5	"
500					

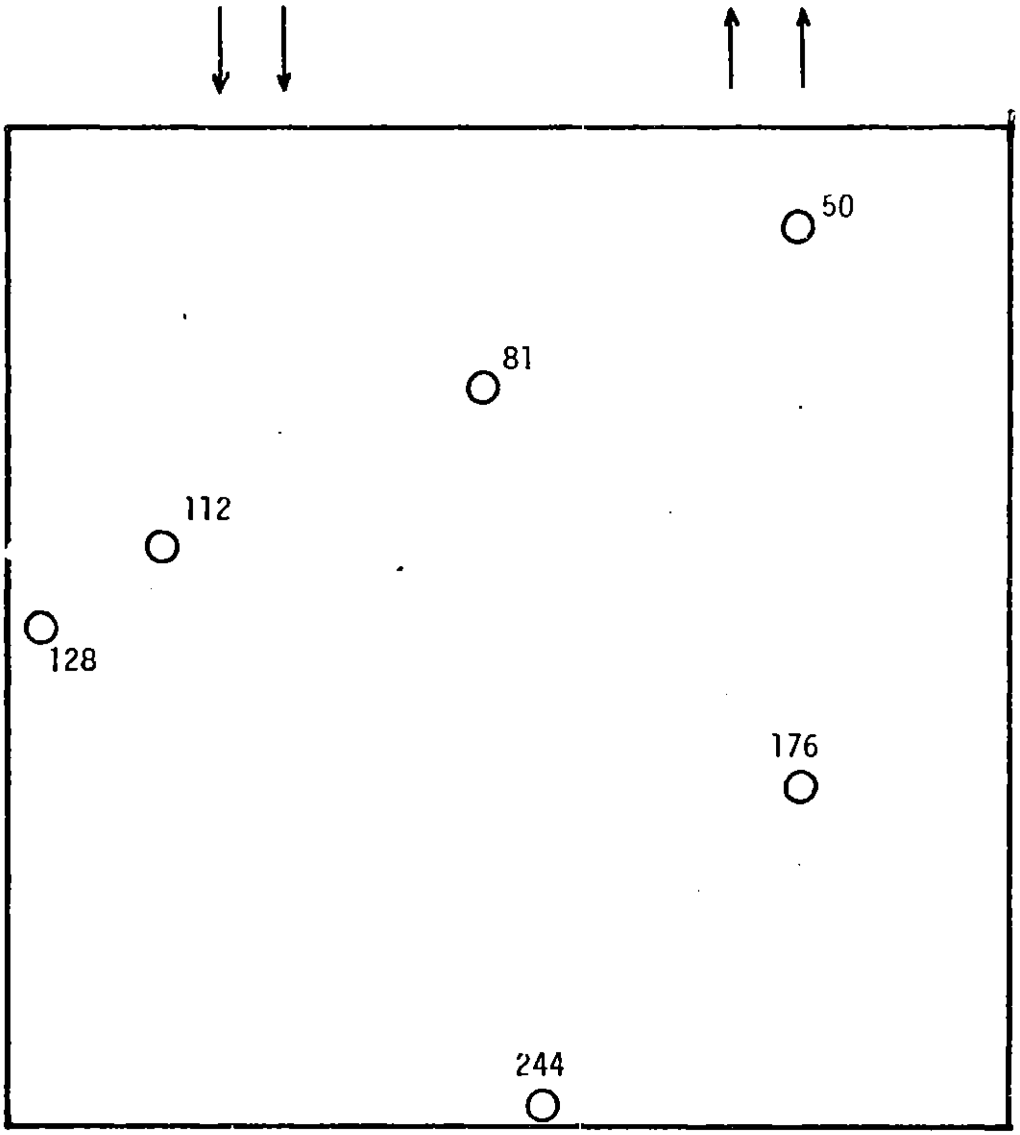


Fig. 5.6 The location of the grid points from which the plots were extracted

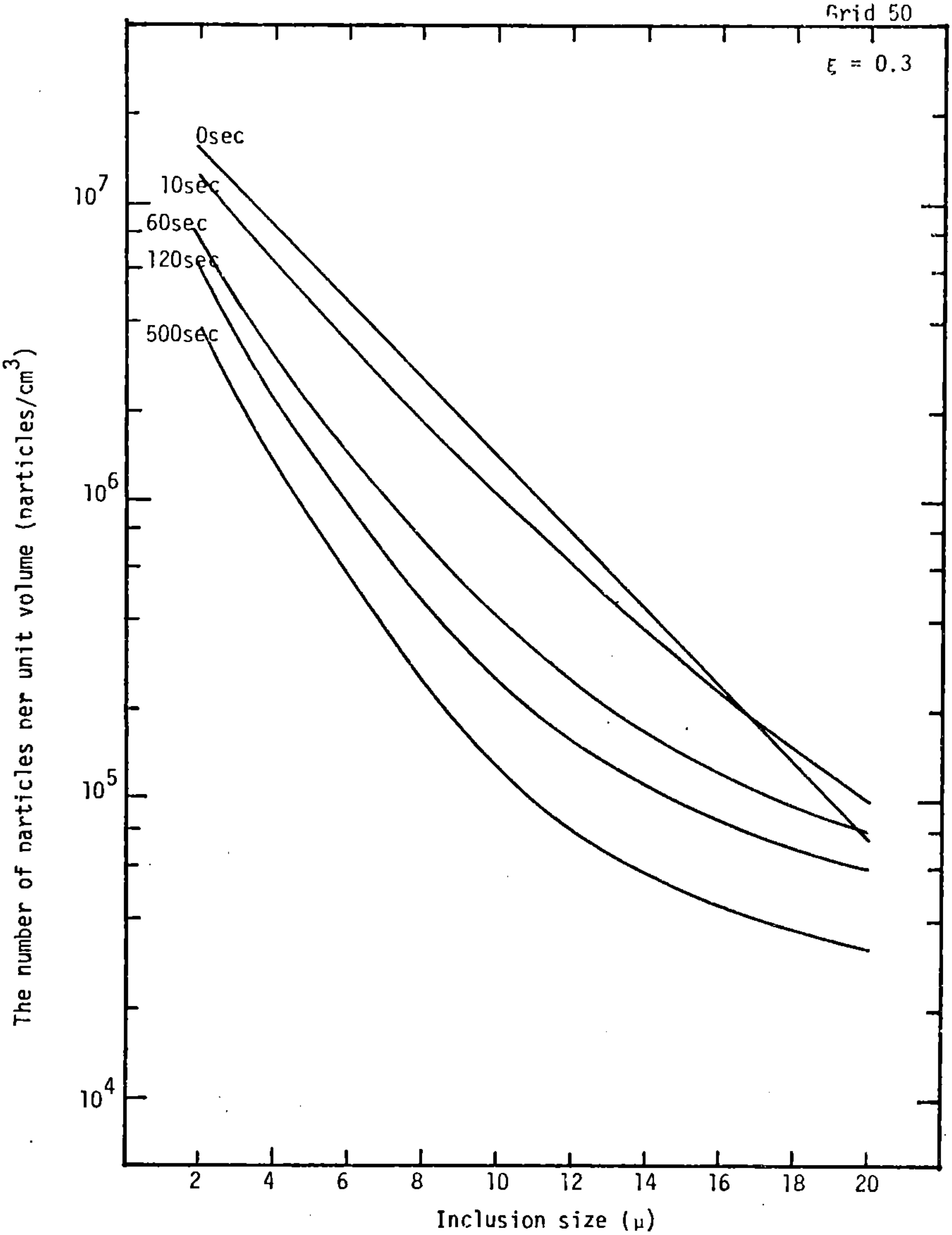


Fig. 5.7 Particle distribution (at grid 50)

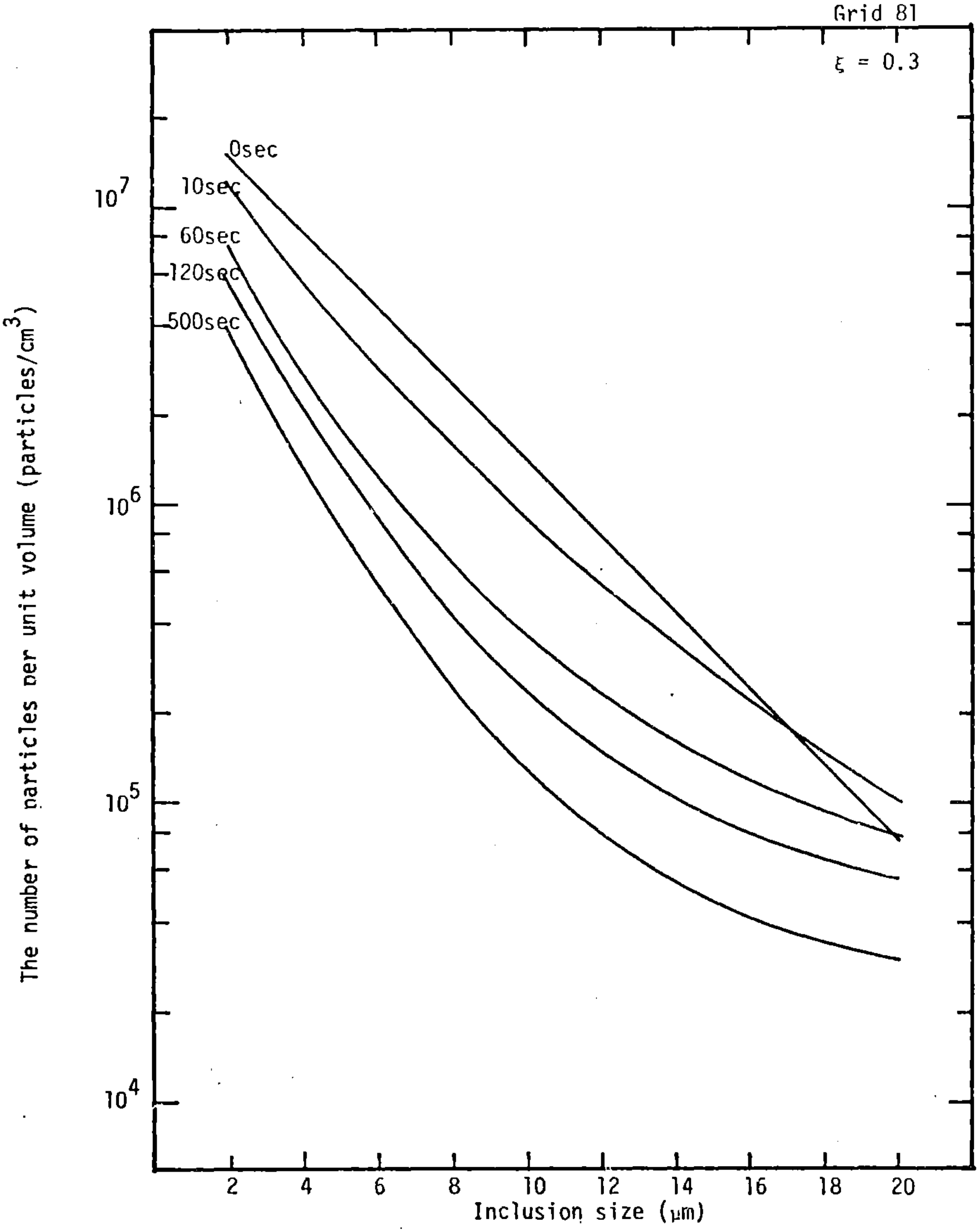


Fig. 5.8 Particle distribution (at grid 81)

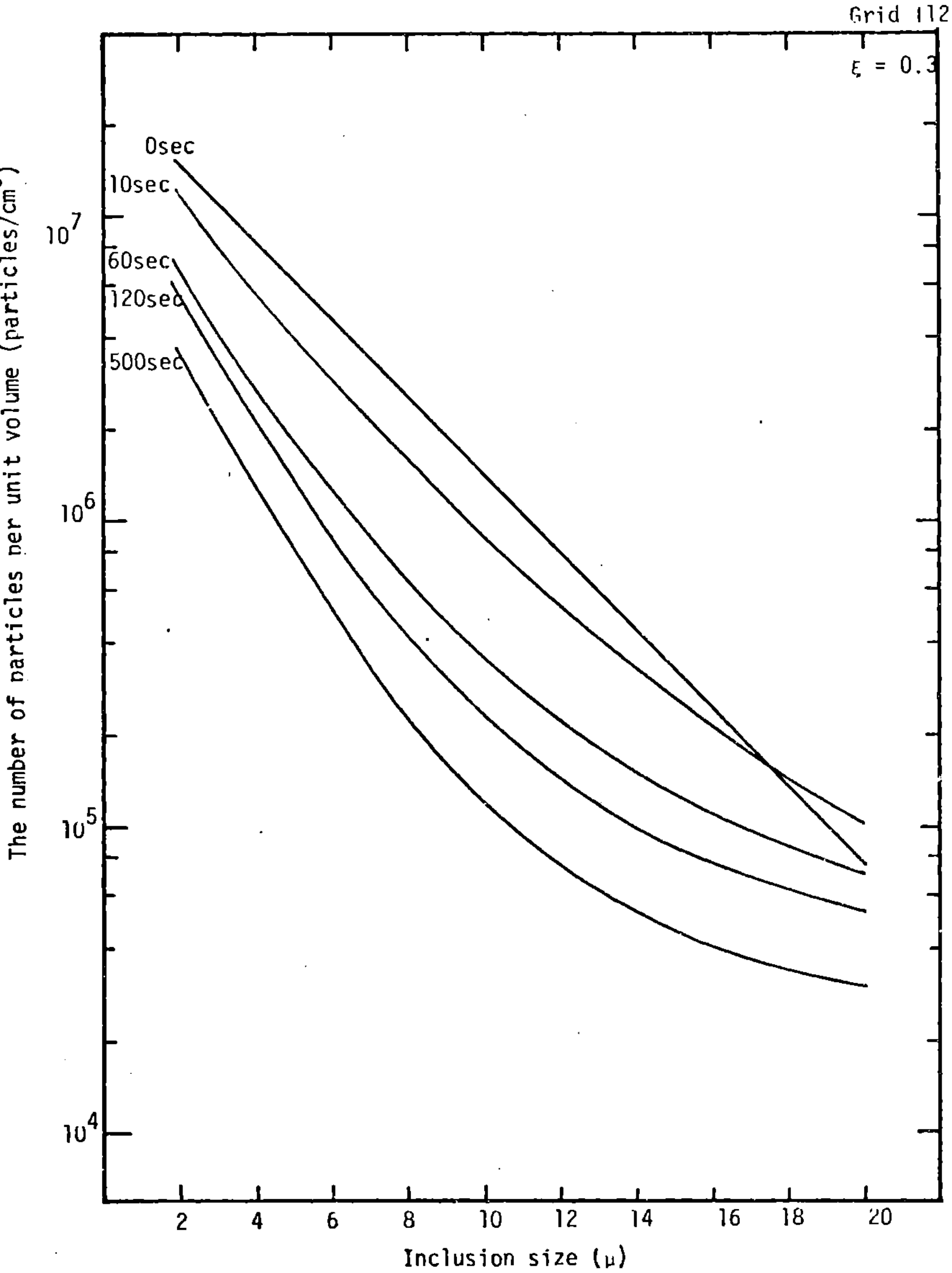


Fig. 5.9 Particle distribution (at grid 112)

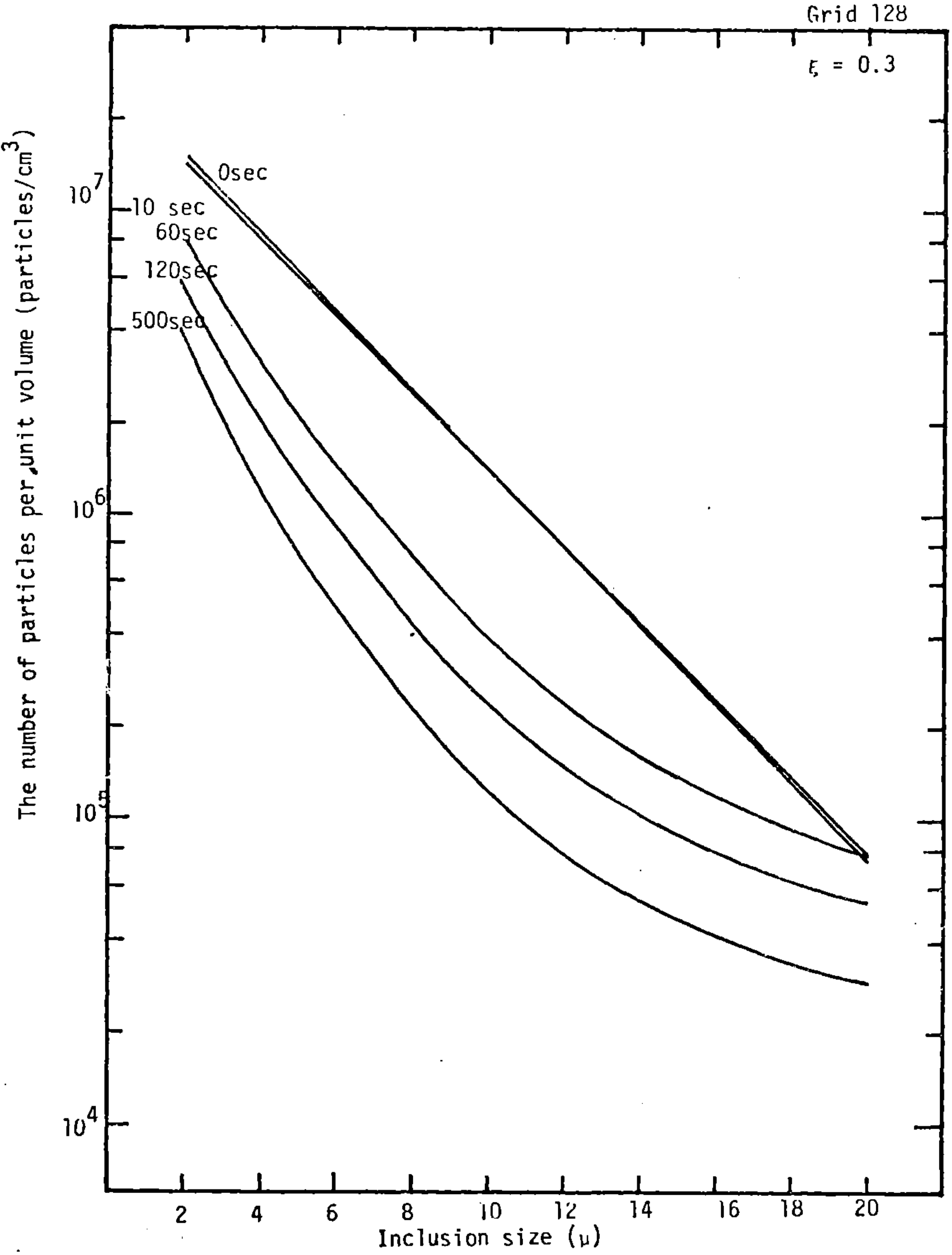


Fig. 10 Particle distribution (at grid 128)

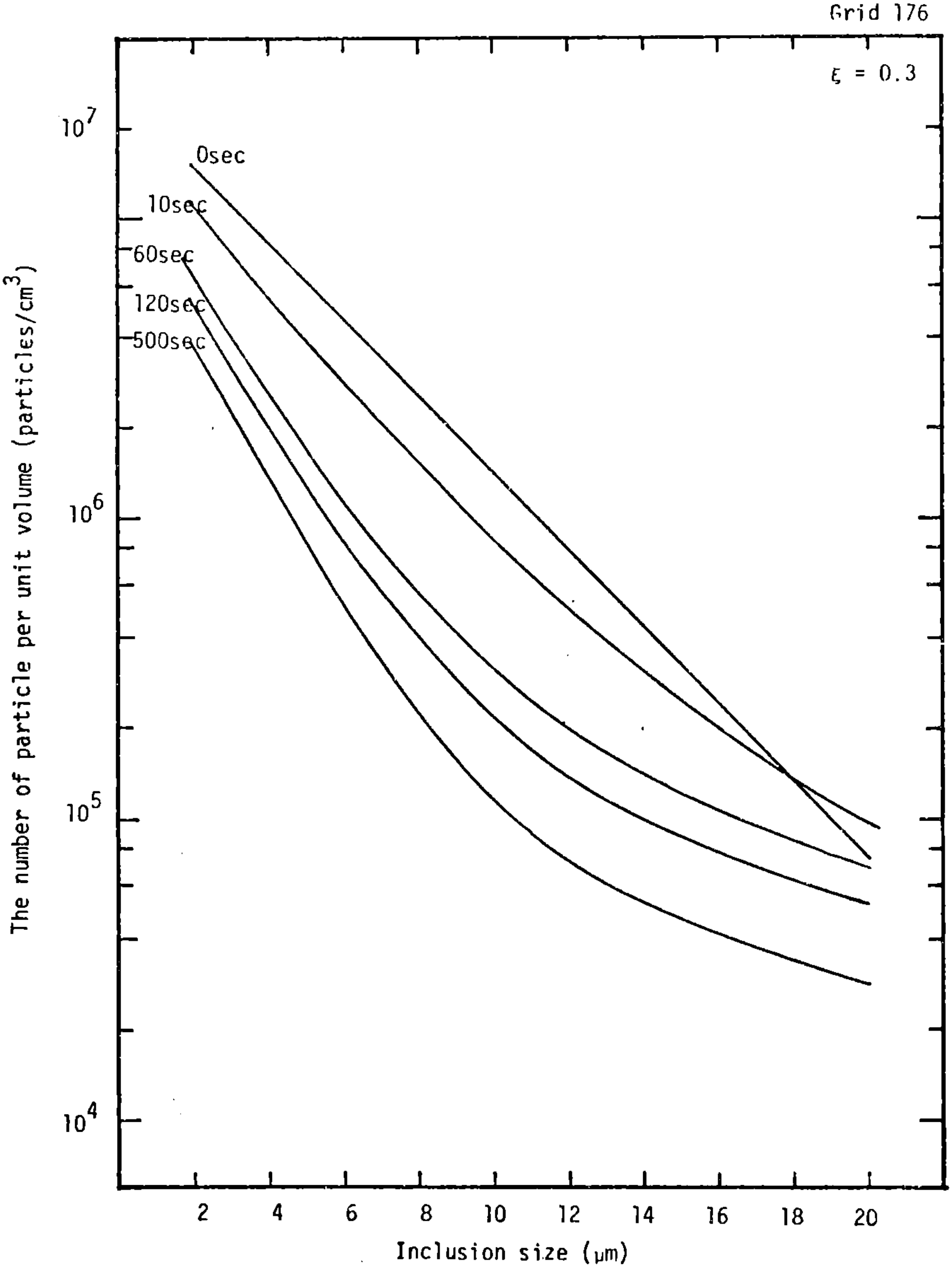


Fig. 5.11 Particle distribution (at grid 176)

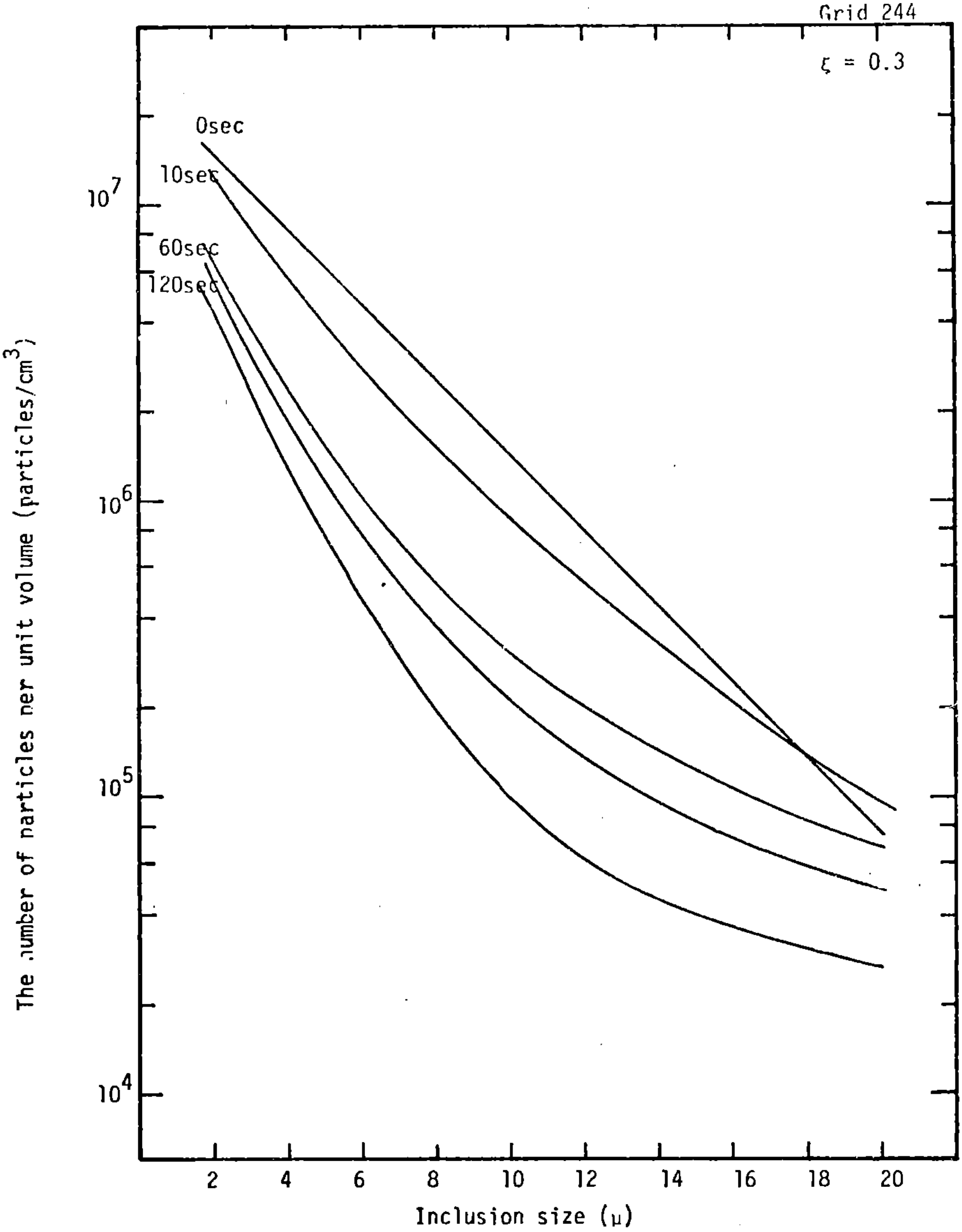


Fig. 5.12 Particles distribution (at grid 244)

the particles which have grown up to a size more than $d \fallingdotseq 20\mu m$ float up and are removed from the system, the coalescence behavior between larger particles is completely negliected. If a wider particle size range is taken, the increase in the number of larger particles would be more significant.

Another feature we can observe from these figures is that the rate of coagulation between intermediate size (i.e. $6\mu m \sim 16\mu m$) particles is relatively high compared with that of smaller particles. This effect is also seen in the calculation of the mass scale (not in the number scale), but at t = 200 sec. The volume fraction of inclusions per class decreases remarkably and this seems to be somewhat contradictory to the experimental results.

The calculated results of P.K. Iyenger and W.O. Philbrook [52] show that the particle distribution decreases in a parallel way in a naturally convected molten steel bath. This seems to come from the fact that they didn't consider the mass conservation but simply applied the Smoulchowski's coagulation model. We also experienced the "parallel decrease in number scale" when the Smoulchowski's coagulation theory was employed. In other words, their assumptions seem to lack the condition of $\frac{dm}{dt} = 0$.

Another calculation was also made by K. Nakanishi et al. [5]. Although they assumed the average turbulent dissipation energy, they obtained similar results to the present calculation. Their results also show that a high reduction rate of particle number appears in the medium size range.

The other feature which the computation results display is the local dependence of the particle reduction rate. At grid point 128 which is adjacent to the wall, the initial reduction rate of oxidized particles is very slow because the convective flow is intense there and the turbulent dissipation energy is very small. However, at time t = 60 sec., the particle distribution seems not to be significantly different from that at other grid points, because the strong convection makes the particle distribution uniform. At grid point 244 where either the flow velocity or the turbulent dissipation energy is small, the initial reduction rate of oxidized particle is not as small as at grid point 128.

Fig. 5.13 - Fig. 5.15 show the spatial distribution of particles of size 2, 10 and 20μm respectively at time t = 120 sec. The particle concentrations are relatively large near the down-leg and decreased towards the bottom of the ladle. As shown in previous section, the turbulent dissipation energy is very high just below the down-leg collide with each other rapidly and soon become larger, Another high particle concentration is seen at the bottom right hand side. In this region, either the turbulent dissipation energy of the fluid velocity is very low and therefore the coagulation rate is low.

Fig. 5.16 - Fig. 5.18 show the rate of reduction for a number of particles. For large particles (20μm radius), it increases about 20-30% at the very initial stage of deoxidation, but decreases again to around the initial value at time t = 60 sec.

On the contrary, for small and medium sized (1μm and 10μm) particles the rate of reduction decreases at the beginning of deoxidation, and falls abruptly to a very low value. According to Lindborg et al. [19], three stages occur in the process of deoxidation. The first stage is the incubation period where ther is a gradual growth of oxidized particles. The second stage is the period of rapid oxygen removal where the largest particles reach a certain size at which point they rapidly float out of the vessel. The final slow stage begins when the remaining large-sized particles are separated from the bath. In the present calculation, the first stage arises from the nature of the modeling. They assumed the 8 size

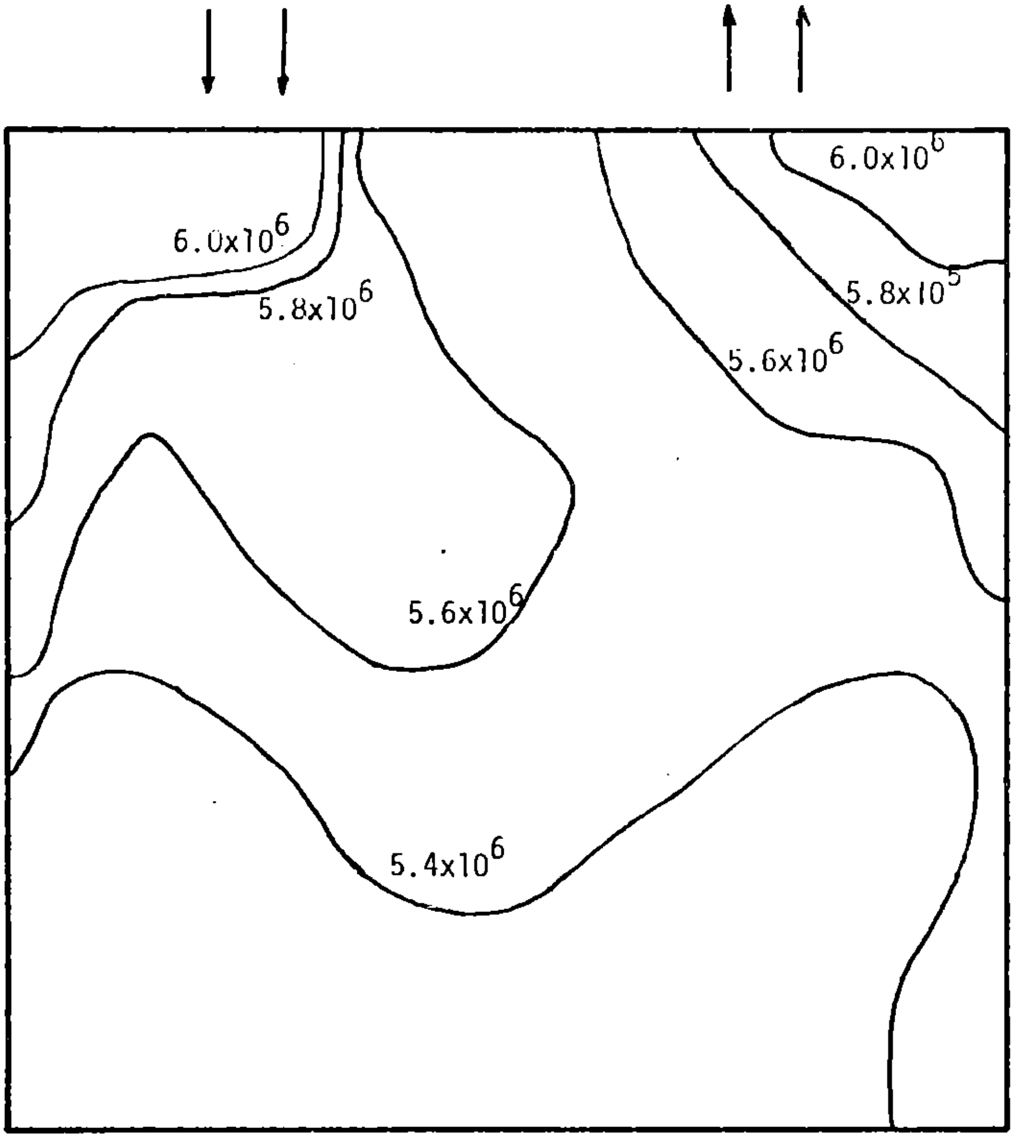


Fig. 5.13 Spatial distribution of the number of the oxidized particles at the time t = 120 sec. (d_p = 1μm).

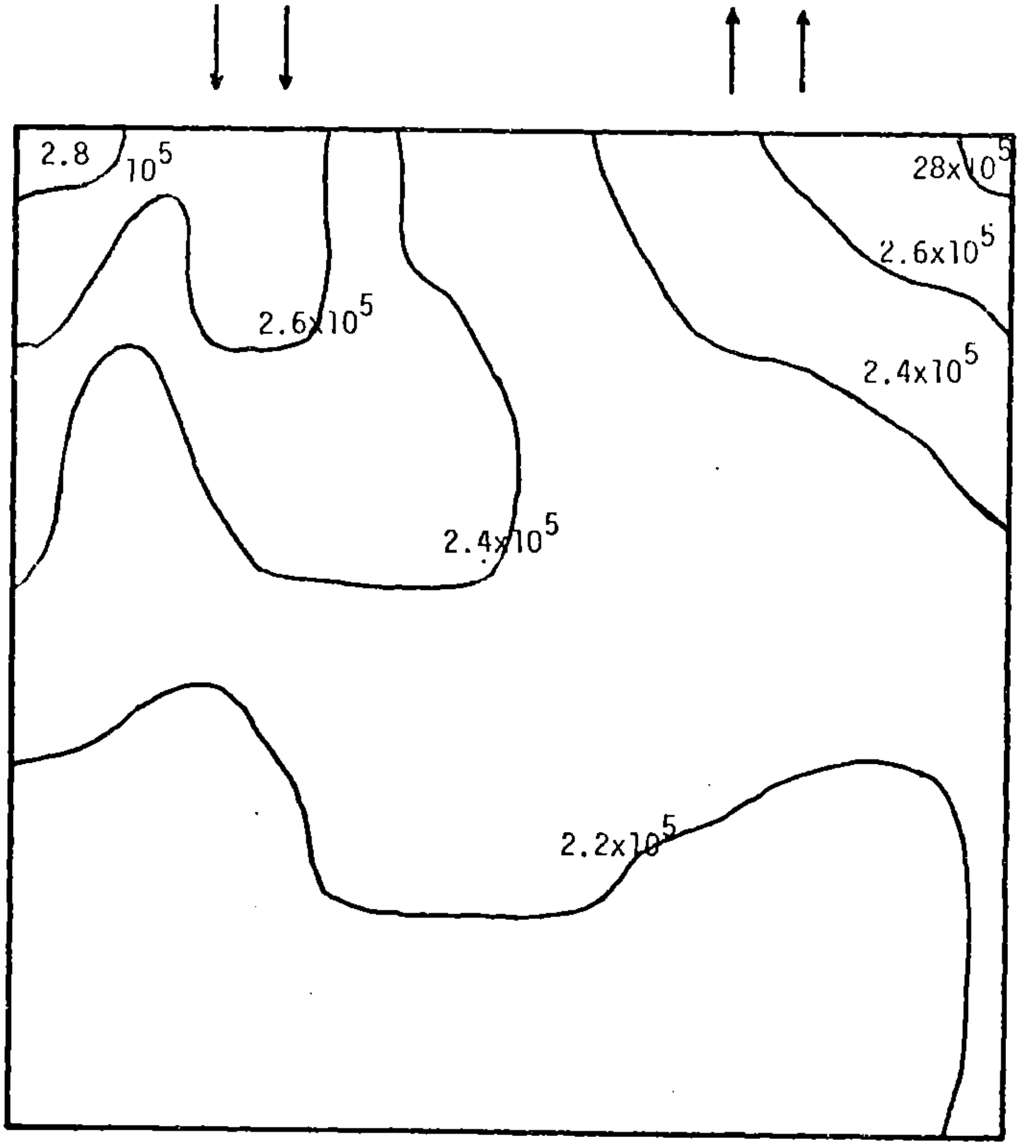


Fig. 5.14 Spatial distribution of the number of the oxidized particles at the time t = 120 sec. (dp = 10μm)

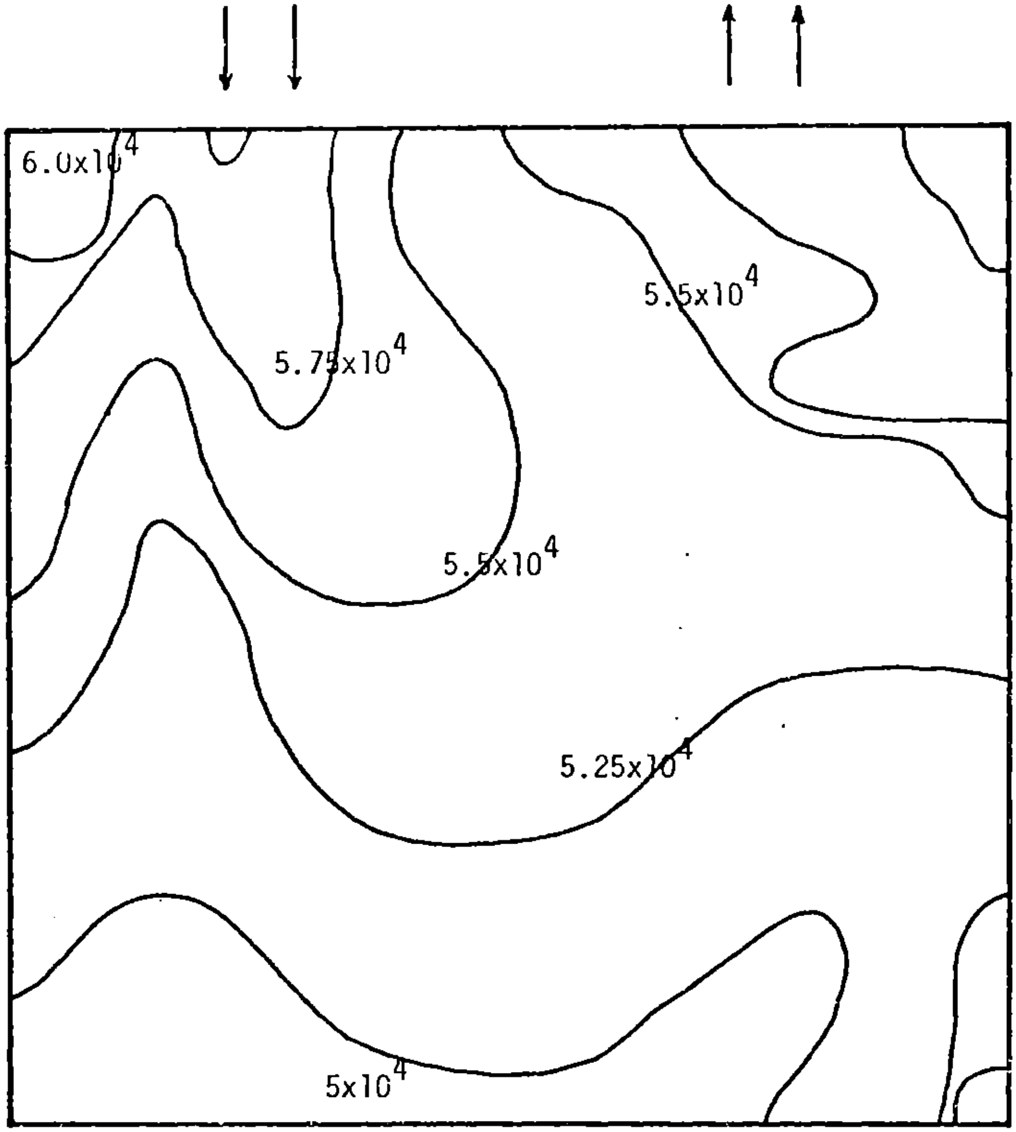


Fig. 5.15 Spatial distribution of the number of the oxidized particles at the time t = 120 sec. (d_p = 20μm).

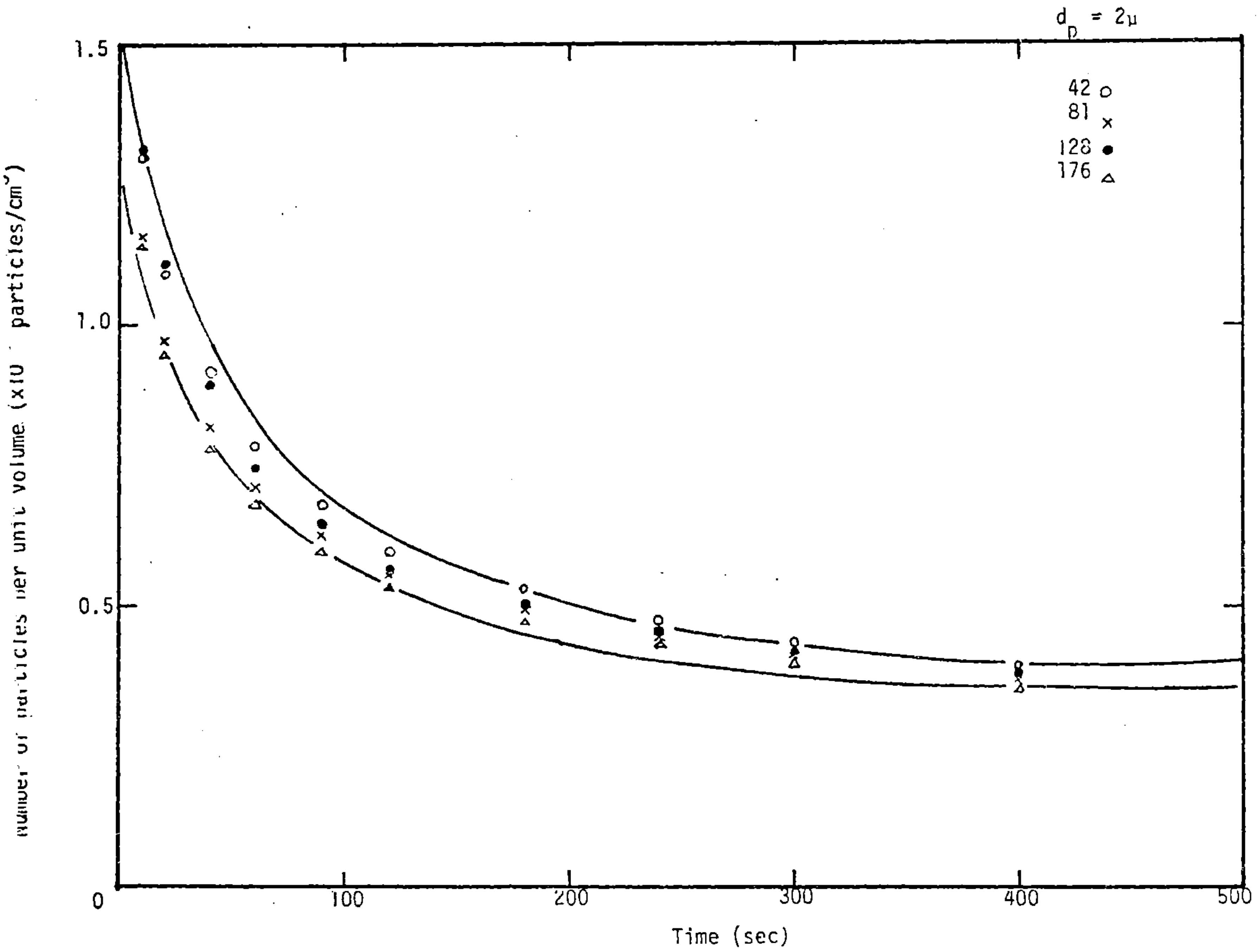


Fig. 5.16 The number of inclusions v_s time ($d_p = 10\mu$)

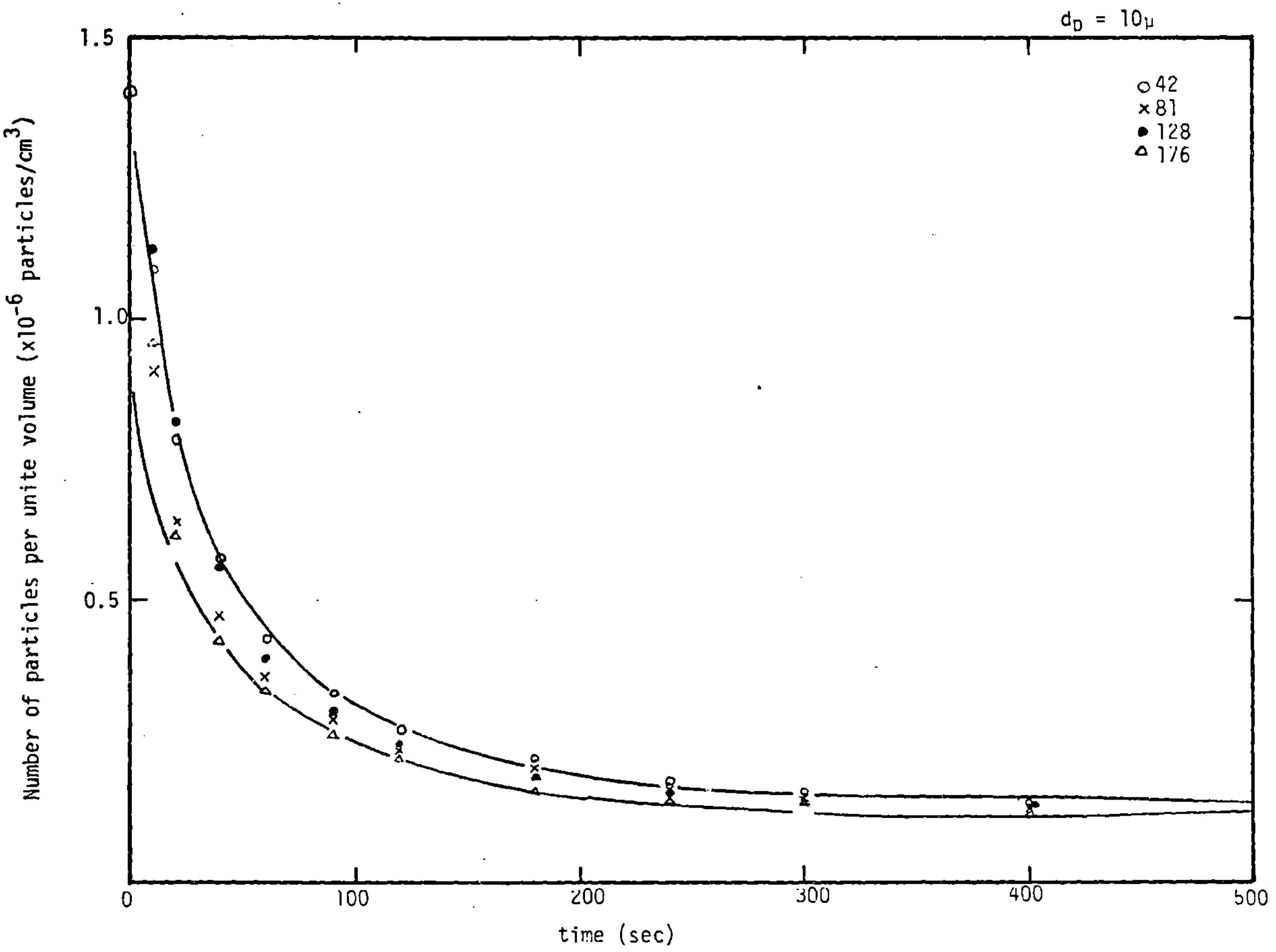


Fig. 5.17 The number of inclusions vs time (d_p = 10μm)

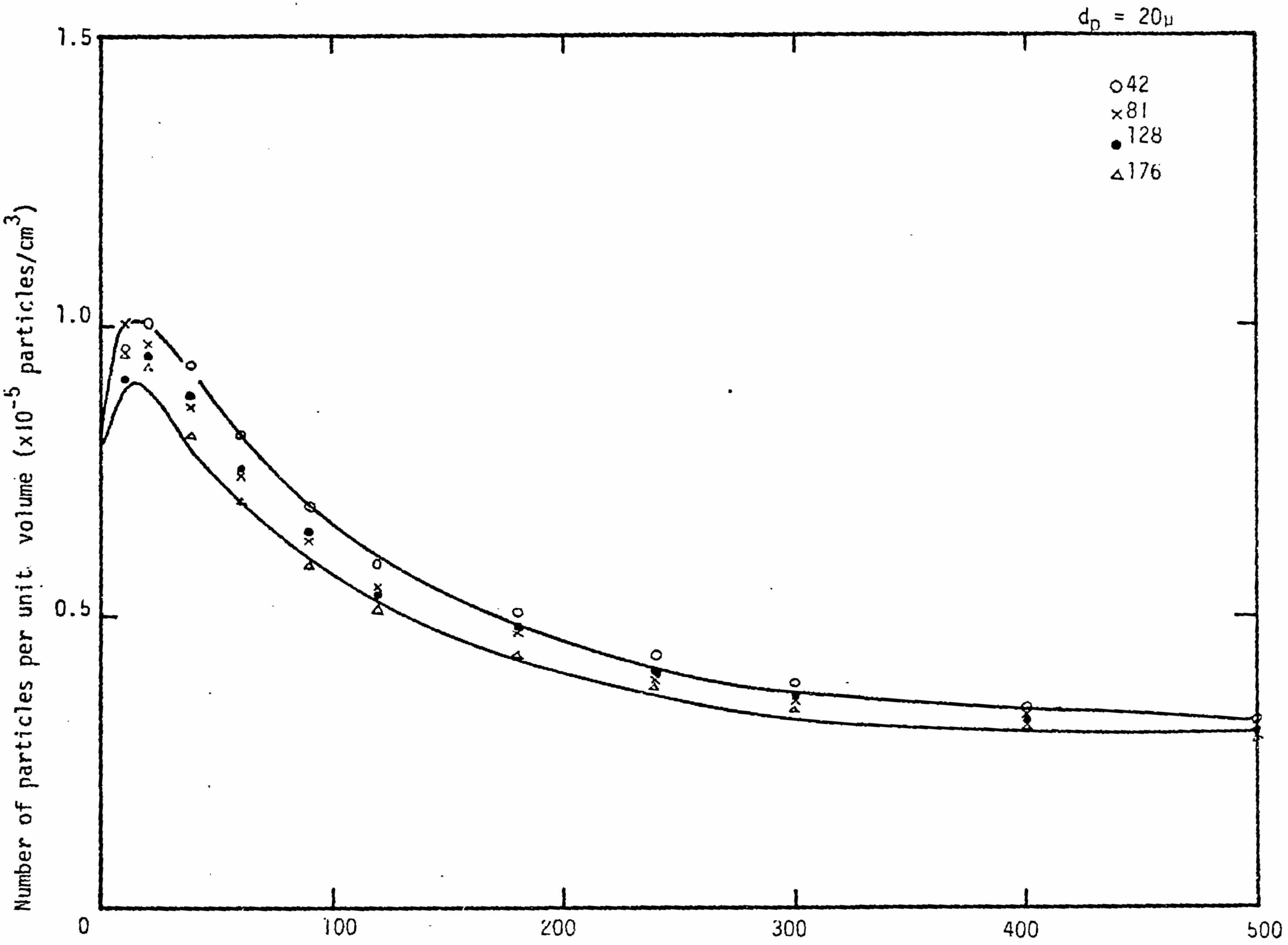


Fig. 5.18 The number of inclusions vs Time (sec) (d_p = 20μm)

classes from 1μm to 128μm, but initial particles have only sizes of 1, 2 and 4μm, so that it takes several minutes for particles to reach the critical size, in their case 32μm. On the contrary, in the presnet calculation the critical size of particles is considered to be 20μm and the particles of size 20μm exist from the beginning of the computation. This may be the reason why the first stage didn't appear. It is very difficult to determine the critical particle sizes at which particles are rapidly separated from the bath. However, it may be said that the first stage will appear if the initial particle size is far smaller than the critical size.

Fig. 5.19 shows the initial coalescence frequency

$$N = 1.67 \left(\frac{\varepsilon}{\nu}\right)^{\frac{1}{2}} (r_1 + r_2)^3 n_1 n_2$$

where ε is taken as 40 erg/cm^3. The highest collision rate occurs for 6μm particles and is almost equilavent to the initial number of 6μm particles. Since the collision rate is proportional to the product of particle concentration and the third power of the sum of their radii, the coagulation rate is extra ordinarily high at initial stage but soon falls to a small value. Therefore, if the large particles are assumed to exist, the initial rate of particle removal is very rapid.

Until now, the disscussion has been made on the basis of particle population, but major experimental results are expressed in mass scale. As Nakanishi [5] said in his paper, there is the discrepancy between the oxygen content obtained by the counting method and the chemical analysis. However, it may be practically meaningful to convert present particle number scale to mass scale,

$$[\%O] = \frac{100\pi M_O \gamma}{6 \Omega \rho_{Fe}} \int_0^{d_{max}} d^3 f(d)\, d(d)$$

$\epsilon = 40\ (\mathrm{cm^2/sec^3})$

d_2 \ d_1	2	4	6	8	10	12	14	16	18	20
2	9.256×10 2.053×10^{5}	3.124×10^{6} 3.973×10^{5}	7.405×10 5.220×10^{5}	1.446×10 5.160×10^{5}	2.470×10^{7} 5.205×10^{5}	3.761×10^{7} 4.762×10^{5}	5.924×10^{7} 3.910×10^{5}	8.435×10^{7} 3.051×10^{5}	1.157×10^{8} 2.256×10^{5}	1.540×10^{8} 1.782×10^{5}
4		7.405×10^{6} 5.350×10^{5}	1.446×10^{7} 5.775×10^{5}	2.470×10 5.455×10^{5}	3.761×10^{7} 4.703×10^{5}	5.924×10 4.023×10^{5}	8.435×10 3.155×10^{5}	1.157×10^{8} 2.310×10^{5}	1.540×10^{8} 1.702×10^{5}	1.997×10 1.275×10^{5}
6			2.470×10^{7} 5.521×10^{5}	3.761×10^{7} 4.550×10^{5}	5.924×10^{7} 3.595×10^{5}	8.435×10^{7} 3.171×10^{5}	1.157×10^{7} 2.313×10^{5}	1.540×10^{7} 1.731×10^{5}	1.997×10^{7} 1.222×10^{5}	2.542×10 8.96×10^{4}
8				5.924×10^{8} 4.005×10^{5}	8.435×10^{8} 3.07×10^{5}	1.157×10^{7} 2.467×10^{5}	2.540×10^{7} 8.56×10^{4}	1.997×10^{7} 1.165×10^{5}	2.542×10^{7} 8.572×10^{4}	3.175×10 6.191×10
10					1.157×10^{7} 2.263×10^{5}	1.540×10^{7} 1.735×10^{5}	1.997×10^{7} 1.234×10^{5}	2.542×10^{7} 8.54×10^{4}	3.175×10^{7} [illegible]	3.905×10 4.10×10^{4}
12						1.997×10^{7} 1.218×10^{5}	2.542×10^{7} 8.948×10^{4}	3.175×10^{7} 6.094×10^{4}	3.905×10^{7} 4.011×10^{4}	4.731×10^{7} 2.563×10^{4}
14							3.175×10^{7} 6.146×10^{5}	3.905×10^{7} 4.224×10^{4}	4.731×10^{7} 2.70×10^{4}	5.654×10^{7} 1.97×10^{4}
16								4.731×10^{7} 2.73×10^{4}	5.654×10^{7} 1.773×10^{4}	6.745×10 1.115×10^{4}
18									6.745×10^{7} 1.140×10^{4}	7.956×10^{7} 7.38×10^{3}
20										7.464×10 5.207×10^{3}

Fig. 5.19 Initial coalescence frequency

where, MO is the atomic weight of oxygen, ρ_{Fe} is the density of the molten iron, Ω is the molar volume of oxide particle and y is the stoicheometric number of oxygen in oxide.

Fig. 5.20 shows the rate of deoxidation in mass scale at the grid point 81 and Fig. 5.21 shows the spatial distribution of oxygen content in the form of oxide.

Fig. 5.22 shows the non-dimensional deoxidation rate.

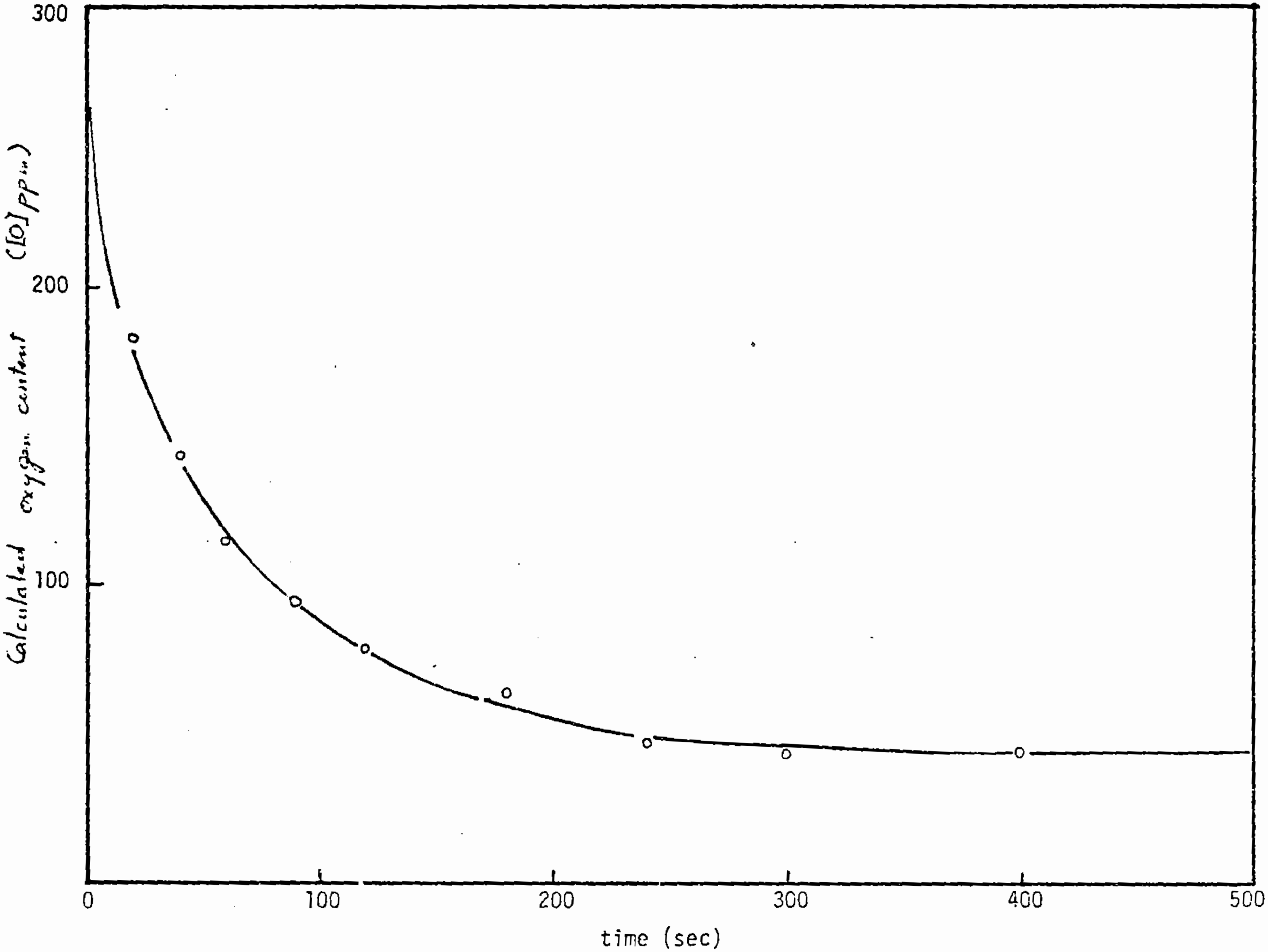


Fig. 5.20 The calculated total inclusion content vs time

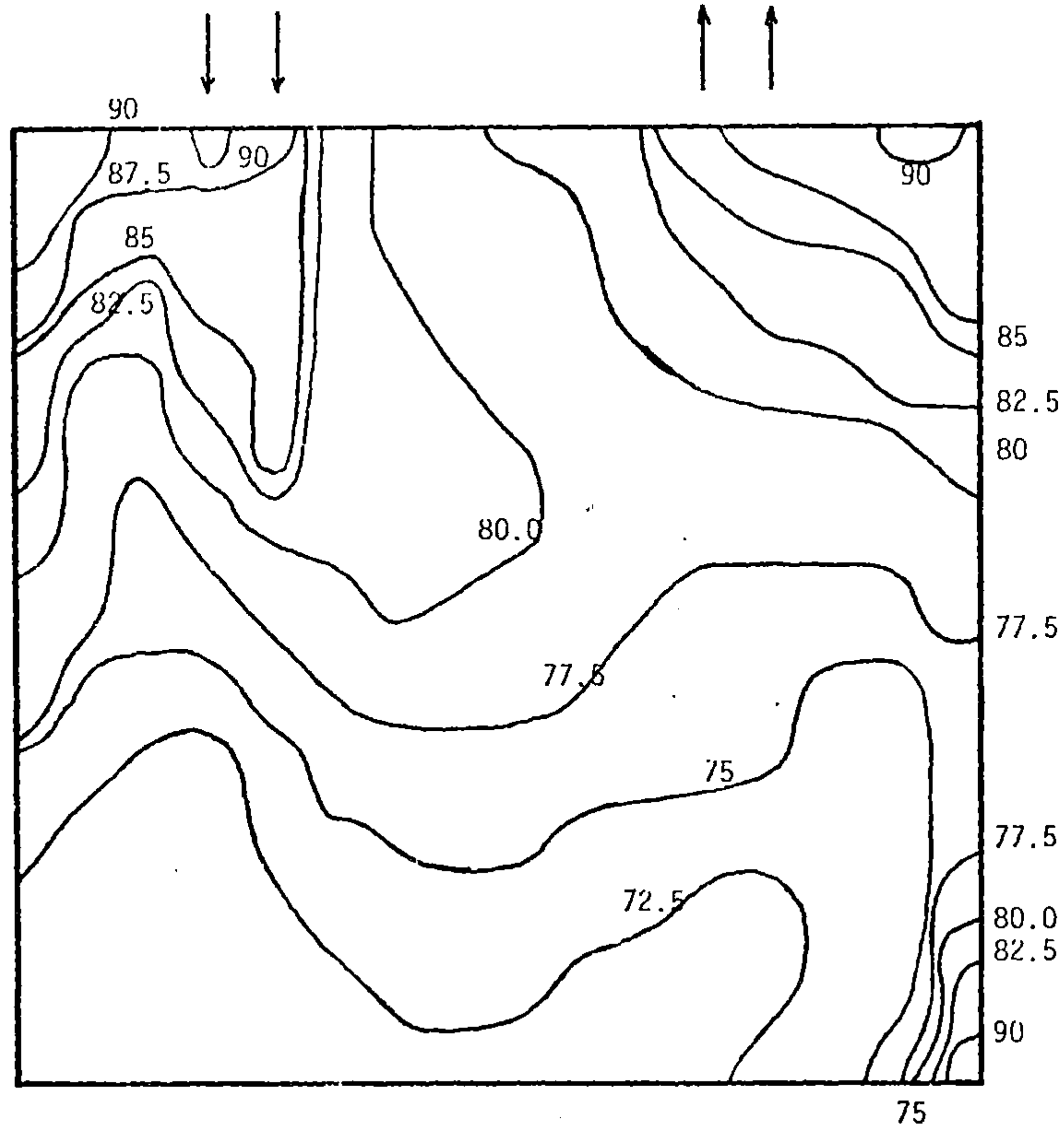


Fig. 5.21 Spatial distribution of oxygen content at the time t = 120 sec. ([O] ppm).

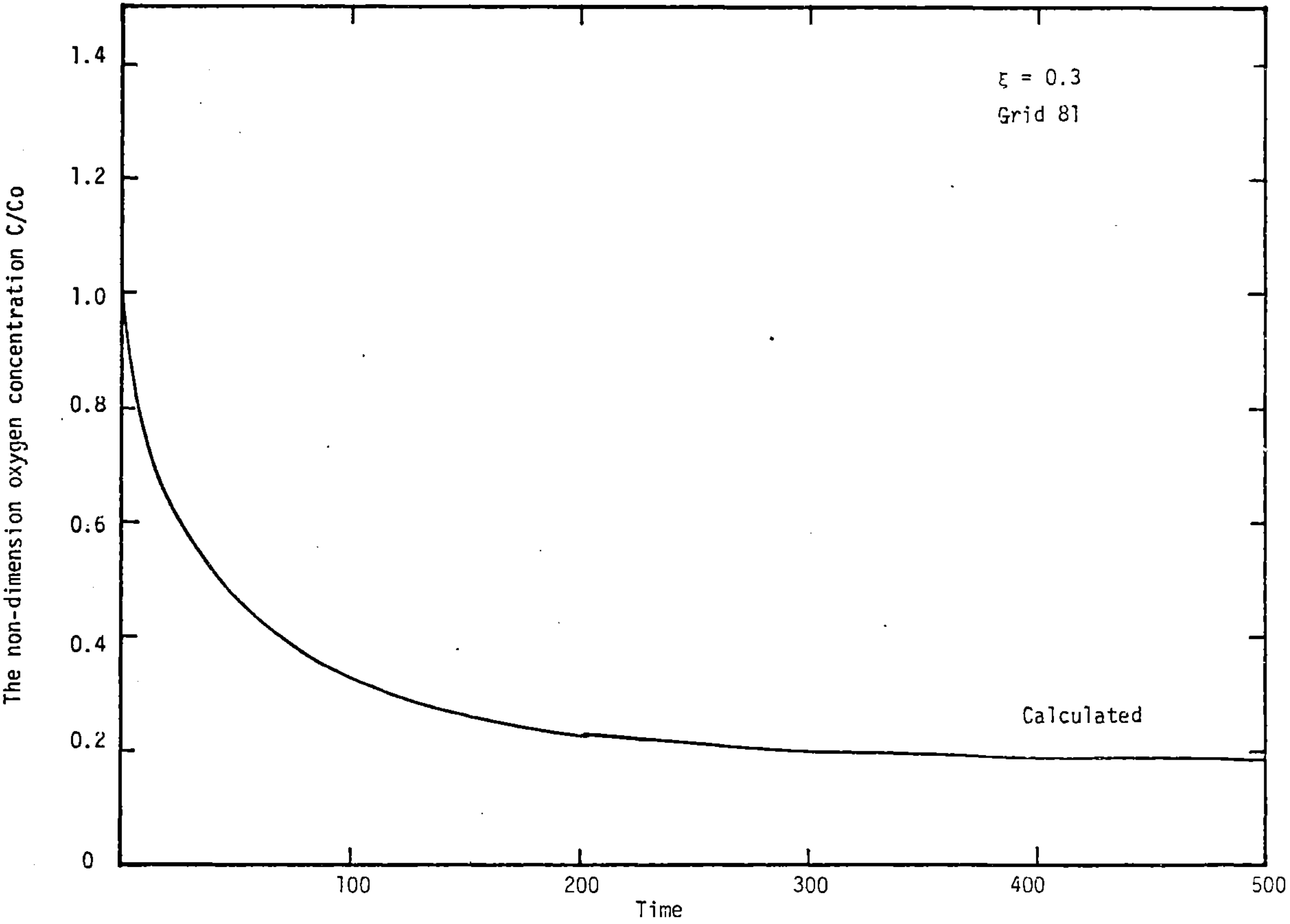


Fig. 5.22 The non-dimension oxygen concentration vs time

Chapter 6 Conclusions

Concluding remarks and some suggestions for future work are made in this chapter.

6.1 Conclusions

A mathematical model has been developed to describe fluid flow and oxidized particle coagulation phenomena in the R-H vacuum degassing system. The program consists of two parts: fluid flow program and particle coagulation program. Regarding the fluid flow calculation, the turbulent Navier-Stokes equations were solved by using a numerical technique developed by Pun and Spalding. The principal findings are succeeded as follows:

1. The computed results indicated that the metal moves quite rapidly in the upper part of the ladle, with maximum velocity ~ 60-70 cm/sec. In the lower part of the ladle the velocities are relatively small but still finite even at the bottom.

2. Two major local recirculating loops appear: one between the two legs and one near the wall of the down-leg side.

3. The metal velocity is quite fast in the vicinity of the vertical walls.

4. The turbulence characteristics, i.e., the kinetic energy of turbulence, the dissipation rate of the kinetic energy of turbulence and the effective viscosity are very large just below the dow leg which is consitent with the velocity field.

5. The effective diffusivity is high just under the dow leg with the maximum value 70 cm/sec^2, but the region of the low effective diffusivity appears between the two legs.

The particle coalscence calculations involved population balance models coupled to the previously computed velocity field. The following principal results are:

1. The time-dependent particle distribution was obtained at each grid point in the ladle. Under the assumption presently used, the reduction rate of particles is rapid for the intermediate size particles because of the high probability to encounter other particles.

2. Regarding the spatial distribution of the particle, the high concentration appears in the vicinity of the dow-leg and the up-leg. The concentration tends to be lower at the lower portion of the ladle except at the corner of bottom and up-leg side wall.

3. The larger particles were found to increase at the very initial stage of the mixing. It is suggested that the larger particles play important role in the reduction of the smaller particles. Possibly the addition of larger particles would contribute to reduce the very small particle inclusions.

6.2 Suggestion for a further study

The present work represents a first attempt at combining population balance models with the representation of turbulent recirulating flows to model model deoxidation kinetics. The results which have been presented indicate that this could be a very fruitful approach to a rather boarder class of problems. The following appear to be rather obvious extensions of the present study:

1. The model could be extended to represent the removal of oxide particles due to collision with the walls of the system.

2. The model could be extended to include a dynamic oxygen balance, which would allow for both the removal of oxygen due to the removal of the inclusions and the addition of oxygen to the system from the walls and or from the atmosphere.

3. The chemical factors which influence the collision effeciency could also be incorporated into the model and finally.

4. While the actual model development was undertaken within the framework of the R-H system, clearly identical consideration could be applied to other deoxidation systems, involving turbulent recirculation flow.

NOMENCLATURE

A_i	Coefficients in the finite-difference equations (i = W,E,N,S)
B	Nucleation function in Table 2.1
b	Distribution function of daughter particles
C_i	Particle density
C_D	Dissipation constant
C_d	Drag coefficient
C_1, C_2	Constants in k-ε model
d_p	Partical diameter
D	Dissipation term for kinetic energy of turbulence
D_a	Brownian diffusional coefficient in Table 2.2
D	Diffusion coefficient
D_i	Diffusion conductance defined by Equ. (4.1.21)
E	Function of wall roughness in Equ. (3.4.16)
E	Energy-spectrum function
$f(\xi,t)$	Number density of particles at ξ, t
f	The friction factor
F_i	Mass flow rate defined by Equ. (4.1.20)
F_L, F_s	Forces acting on the sphere in Equations (2.6.1) and (2.6.2)
G	The function for diffusional growth
$h(x,m,t)$	Production term in Equ. (2.4.4)
k	Mass transfer coefficient for particles
K	Kinetic energy of turbulence
ℓ	Characteristic length scale of turbulence
ℓ_ε	Dissipation length in Equ. (2.7.10)
m	Mass scale for number density function
n_i	Number of particles in i-th class

N_{grad}	Rate of particle coalescence by velocity gradient collision
N_{turb}	Rate of particle coalescence by turbulent collision
p	Time-smoothed static pressure
P_i, Q_i	Coefficients for pressure correction
P_e	Peclet number
r	Radius of particles
S^+	Non-dimensional stopping length for a particle
S_ϕ	Source term for variable ϕ
S_ϕ	$= S_u + S_p\phi_p$
t	Time
u	X-directional component of velocity
V	Y-directional component of velocity
v	Kolmogolov's velocity scale
W_w	Radial component of the relative velocity around a particle
X_s	Height of the ladle
Y_s	Diameter of a ladle
y, y_+	Dimensional and dimensionless distance from the wall

Greek

α	Relaxation factor
α_{ij}	Coalescence function between i-th and j-th class
$\alpha(x,m,t)$	Coalescence function in Table 2.1
$\beta(x,m,t)$	Breakage function of particles in Table 2.1
Γ	Velocity gradient around a particle in Equ. (2.6.15)
Γ_ϕ	Diffusion Coefficient for the general variable
ε	Rate of dissipation of kinetic energy of turbulence
	von Karman's constant
λ, λ_E	Lagrangian or Eulerian microscale, respectively

ν	Kinetic viscosity
ρ	Density
ρ_f	Density of fluid
ρ_p	Density of particles
τ_1,τ_2	Stokes' forces
$\tau_w\ \tau_o$	Shear stress near the wall
μ,μ_t	Laminar and turbulent viscosity of fluid
μ_{eff}	Effective viscosity
η	Kolmogorov's scale length
ϕ	General variable (- u,v,k,)
ω	Angular frequency

APPENDIX A

THE COMPUTER PROGRAM FOR FLUID FLOW CALCULATION

```
      BLOCK DATA                                                        CAS00010
      COMMON                                                            CAS00020
     1/CASE1/UINLET,FLOWIN,RPIPE,XPIPE,FXSTEP,HINLET,HWALL              CAS00030
     2/DNY/ DYG(22),DYV(22),FV(22),FVNODE(22),R(22),RDYG(22),RDYV(22)   CAS00040
     2,RSYG(22),RSYV(22),RV(22),RVCB(22),SYG(22),SYV(22),Y(22),YV(22)   CAS00050
     3/DNYONX/AE(22),AN(22),AP(22),AS(22),AW(22),C(22),D(22),DIFE(22)   CAS00060
     3,DIFN(22),DUW(22), DIFW(22),DU(22),DV(22),EMUE(22),EMUN(22)       CAS00070
     3          ,EMUW(22),HCONE(22),HCONN(22),            HCONW(22)     CAS00080
     3,PHIOLD(22),RHOE(22),RHON(22),           RHOW(22),SP(22),SU(22)   CAS00090
     3,VOLUME(22),CONN(22),CONS(22),CONE(22),CONW(22),ESMPHI(22)        CAS00100
     4/DNX/ DXG(22),DXU(22),FU(22),FUNODE(22),KOUNT(22),RDXG(22)        CAS00110
     4,RDXU(22),RSXG(22),RSXU(22),STORE(22),SXG(22),SXU(22),X(22),XU(22)CAS00120
     5/DJPHI/ IEW(10),ILAST(10),IMON(10),IXNY(10),IZERO(10)             CAS00130
     5,JGROUP(10),KADSOR(10),KSOLVE(10),KRS(10),RELAX(10),RSREF(10)     CAS00140
     5,RSSUM(10),ITITLE(10)                                             CAS00150
      COMMON                                                            CAS00160
     6/D0/CCHECK,DP,FLOWPC,FLOWST,FLOWUP,GREAT,ILINE,IPLRS,IPREF,IPRINT CAS00170
     6,ISTEP ,IX,IX1NY,IX1NY1,IX2NY2,IXMON,IXP1,IXPREF,IYMON,IYPREF     CAS00180
     6,JEMU,JH,JLAST,JLIM1,JLIM2,JLIM3,JLIM4,JP,JPP,JRHO                CAS00190
     6,JU,JV,JVP1,KINPRI,KMPA,KRAD,KRHOMU,KTEST,LABPHI                  CAS00200
     6,LASTEP,LINEF,LINEL,NEQ,NEQP1                                     CAS00210
     6,NODEF,NODEF1,NODEL,NODEL1,NODLP1,NTDMA,NUMCOL                    CAS00220
     6,NX,NXMAX,NXM1,NXM2,NXYG,NXYP,NXYU,NXYV                           CAS00230
     6,NY,NYMAX,NYM1,NYM2,PI,RSCHEK,RSMAX,TINY                          CAS00240
      COMMON/PROP/EMUREF,PRL(10),PRT(10),RHOREF                         CAS00250
      COMMON/D2D1/ARSL(22,10),RSLINE(22,10)                             CAS00260
      COMMON/D2D2/U(462),V(462),TKE(484),TED(484),H(484),PP(22),P(400)  CAS00270
     7 ,RHO(484),EMU(484)                                               CAS00280
     7,INLY(10),IOUT(10),KIN,KOUT,RELTKE,RELTED,ISTCH                   CAS00290
      COMMON                                                            CAS00300
     9/TURB/C1,C2,CD,SQRTCD,CD25,ECONST,CTAUTW,CYPTW,TAUTW1(22)         CAS00310
     9,TAUTW2(22),YPUST1(22),YPUST2(22)                                 CAS00320
     9,TAULW(22),XPUSLW(22),CTAULW,CXPLW                                CAS00330
     9,GENK(22),FACTKE,FACTED,JTKE,JTED,CAPPA                           CAS00340
     9,INLY1,INLY2,IOUT1,IOUT2,I1M1,I2P1,I3M1,I4P1                      CAS00350
      COMMON/ABC/AREAE                                                  CAS00360
      DIMENSION F(3766)                                                 CAS00370
      DIMENSION DIFS(22),EMUS(22),HCONS(22),RHOS(22)                    CAS00380
      EQUIVALENCE (HCONS(2),HCONN(1))                                   CAS00390
      EQUIVALENCE (DIFS(2),DIFN(1)), (EMUS(2),EMUN(1))                  CAS00400
      EQUIVALENCE (RHOS(2),RHON(1)), (AREAE,AREAW)                      CAS00410
      EQUIVALENCE (F(1),U(1))                                           CAS00420
      DIMENSION A(22),B(22)                                             CAS00430
      EQUIVALENCE(A(1),AN(1)),(B(1),AS(1))                              CAS00440
CHAPTER 1 -------------- GENERAL,FLOW PARAMETERS                        CAS00450
      DATA GREAT,TINY,PI/1.E30,  1.E-30, 3.1415926/                     CAS00460
      DATA RPIPE,XPIPE,UINLET,HINLET,HWALL/                             CAS00470
     1  250.,250.,72.,0.0,0.0/                                          CAS00480
      DATA KTEST/0/                                                     CAS00490
CHAPTER 2 -------------- GRID                                           CAS00500
      DATA NXMAX,NYMAX/22,22/                                           CAS00510
      DATA KRAD/1/                                                      CAS00520
      DATA FXSTEP/1.0/                                                  CAS00530
CHAPTER 3 -------------- VARIABLES                                      CAS00540
      DATA JU, JV,JTKE,JTED,JH,JPP,JP,JRHO,JEMU,JLAST/                  CAS00550
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     1   1.  2.    3.  4. 5.   6.   7.  8.  9.  9/                     CAS00560
      DATA NEQ/4/                                                       CAS00570
      DATA KSOLVE/4*1,0,1,1,0,1,0/                                      CAS00580
      DATA KADSOR/2*0,2*1,6*0/                                          CAS00590
      DATA KRS/4*1,0,1,4*0/                                             CAS00600
CHAPTER 4 -------------- PROPERTY DATA                                  CAS00610
      DATA RHOREF,EMUREF/7.2,0.06/                                      CAS00620
      DATA PRL,PRT/12*1.,0.9,7*1.0/                                     CAS00630
CHAPTER 5 -------------- STARTING PREPARATIONS                          CAS00640
      DATA IXPREF,IYPREF/2,2/                                           CAS00650
      DATA KINPRI/0/                                                    CAS00660
CHAPTER 6 -------------- STEP CONTROL                                   CAS00670
CHAPTER 7 -------------- BOUNDARY CONDITIONS                            CAS00680
      DATA C1,C2,CD,CAPPA,ECONST/                                       CAS00690
     1  1.43,1.92,0.09,0.4,9.0/                                         CAS00700
      DATA  SQRTCD,CD25/  0.3,0.54722/                                  CAS00710
      DATA  FACTKE,FACTED/0.005,0.03/                                   CAS00720
CHAPTER 8 -------------- ADVANCE                                        CAS00730
      DATA NTDMA/1/                                                     CAS00740
CHAPTER 9 -------------- COMPLETE                                       CAS00750
CHAPTER 10 ------------- ADJUST                                         CAS00760
      DATA KMPA/0/                                                      CAS00770
CHAPTER 11 ------------- PRINT                                          CAS00780
      DATA NUMCOL/10/                                                   CAS00790
CHAPTER 12 ------------- DECIDE                                         CAS00800
      DATA LASTEP/100/                                                  CAS00810
      END                                                               CAS00820
C     MAIN PROGRAM                                                      CAS00830
      COMMON                                                            CAS00840
     1/CASE1/UINLET,FLOWIN,RPIPE,XPIPE,FXSTEP,HINLET,HWALL              CAS00850
     2/DNY/ DYG(22),DYV(22),FV(22),FVNODE(22),R(22),RDYG(22),RDYV(22)   CAS00860
     2,RSYG(22),RSYV(22),RV(22),RVCB(22),SYG(22),SYV(22),Y(22),YV(22)   CAS00870
     3/DNYONX/AE(22),AN(22),AP(22),AS(22),AW(22),C(22),D(22),DIFE(22)   CAS00880
     3,DIFN(22),DUW(22), DIFW(22),DU(22),DV(22),EMUE(22),EMUN(22)       CAS00890
     3          ,EMUW(22),HCONE(22),HCONN(22),          HCONW(22)       CAS00900
     3,PHIOLD(22),RHOE(22),RHON(22),         RHOW(22),SP(22),SU(22)     CAS00910
     3,VOLUME(22),CONN(22),CONS(22),CONE(22),CONW(22),ESMPHI(22)        CAS00920
     4/DNX/ DXG(22),DXU(22),FU(22),FUNODE(22),KOUNT(22),RDXG(22)        CAS00930
     4,RDXU(22),RSXG(22),RSXU(22),STORE(22),SXG(22),SXU(22),X(22),XU(22)CAS00940
     5/DJPHI/ IEW(10),ILAST(10),IMON(10),IXNY(10),IZERO(10)             CAS00950
     5,JGROUP(10),KADSOR(10),KSOLVE(10),KRS(10),RELAX(10),RSREF(10)     CAS00960
     5,RSSUM(10),ITITLE(10)                                             CAS00970
      COMMON                                                            CAS00980
     6/D0/CCHECK,DP,FLOWPC,FLOWST,FLOWUP,GREAT,ILINE,IPLRS,IPREF,IPRINT CAS00990
     6,ISTEP ,IX,IX1NY,IX1NY1,IX2NY2,IXMON,IXP1,IXPREF,IYMON,IYPREF     CAS01000
     6,JEMU,JH,JLAST,JLIM1,JLIM2,JLIM3,JLIM4,JP,JPP,JRHO                CAS01010
     6,JU,JV,JVP1,KINPRI,KMPA,KRAD,KRHOMU,KTEST,LABPHI                  CAS01020
     6,LASTEP,LINEF,LINEL,NEQ,NEQP1                                     CAS01030
     6,NODEF,NODEF1,NODEL,NODEL1,NODLP1,NTDMA,NUMCOL                    CAS01040
     6,NX,NXMAX,NXM1,NXM2,NXYG,NXYP,NXYU,NXYV                           CAS01050
     6,NY,NYMAX,NYM1,NYM2,PI,RSCHEK,RSMAX,TINY                          CAS01060
      COMMON/PROP/EMUREF,PRL(10),PRT(10),RHOREF                         CAS01070
      COMMON/D2D1/ARSL(22,10),RSLINE(22,10)                             CAS01080
      COMMON/D2D2/U(462),V(462),TKE(484),TED(484),H(484),PP(22),P(400)  CAS01090
     7 ,RHO(484),EMU(484)                                               CAS01100
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     7 ,INLY(10),IOUT(10),KIN,KOUT,RELTKE,RELTED,ISTCH                  CAS01110
      COMMON                                                            CAS01120
     9/TURB/C1,C2,CD,SQRTCD,CD25,ECONST,CTAUTW,CYPTW,TAUTW1(22)         CAS01130
     9,TAUTW2(22),YPUST1(22),YPUST2(22)                                 CAS01140
     9,TAULW(22),XPUSLW(22),CTAULW,CXPLW                                CAS01150
     9,GENK(22),FACTKE,FACTED,JTKE,JTED,CAPPA                           CAS01160
     9,INLY1,INLY2,IOUT1,IOUT2,I1M1,I2P1,I3M1,I4P1                      CAS01170
      COMMON/ABC/AREAE                                                  CAS01180
      DIMENSION F(3766)                                                 CAS01190
      DIMENSION DIFS(22),EMUS(22),HCONS(22),RHOS(22)                    CAS01200
      EQUIVALENCE (DIFS(2),DIFN(1)), (EMUS(2),EMUN(1))                  CAS01210
      EQUIVALENCE (RHOS(2),RHON(1)), (AREAE,AREAW)                      CAS01220
      EQUIVALENCE (HCONS(2),HCONN(1))                                   CAS01230
      EQUIVALENCE (F(1),U(1))                                           CAS01240
      DIMENSION A(22),B(22)                                             CAS01250
      EQUIVALENCE(A(1),AN(1)),(B(1),AS(1))                              CAS01260
CHAPTER 1  1  1  1  1    PRELIMINARIES    1  1  1  1  1  1  1  1  1  1  CAS01270
CASE1..... LAMINAR, UNIFORM-PROPERTY, DEVELOPING FLOW IN A PIPE         CAS01280
COMMENT.............    ALL NUMERICAL DATA ARE PUT IN VIA BLOCK DATA    CAS01290
      READ(5,9860) KTEST                                                CAS01300
      READ(5,9860) NX,NY                                                CAS01310
      READ(5,9850) (X(I),I=1,NX)                                        CAS01320
      READ(5,9850) (Y(I),I=1,NY)                                        CAS01330
      READ(5,9850) (RELAX(I),I=1,10)                                    CAS01340
      READ(5,9860) NTDMA,LASTEP,KSWEEP,NOUTP1,ISTEP1                    CAS01350
      READ(5,9860) IPLRS,IPRINT                                         CAS01360
      READ(5,9850) RSCHEK,CCHECK,RSFCHE,RSFC2                           CAS01370
      READ(5,9870) TKEINP,TEDINP                                        CAS01380
      READ(5,9860) KIN,KOUT                                             CAS01390
      READ(5,9860) (INLY(I),I=1,KIN)                                    CAS01400
      READ(5,9860) (IOUT(I),I=1,KOUT)                                   CAS01410
      READ(5,9850) RLEG                                                 CAS01420
      READ(5,9860) IXMON,IYMON                                          CAS01430
      READ(5,9860) ISTCH                                                CAS01440
      READ(5,9850) RELTKE,RELTED                                        CAS01450
 9850 FORMAT(8F10.0)                                                    CAS01460
 9860 FORMAT(10I5)                                                      CAS01470
 9870 FORMAT(5E10.3)                                                    CAS01480
      ISTEP=0                                                           CAS01490
      ILINE=0                                                           CAS01500
      DO 9800 JPHI=1,JLAST                                              CAS01510
      JGROUP(JPHI)=0                                                    CAS01520
      DO 9800 IX=1,NX                                                   CAS01530
 9800 RSLINE(IX,JPHI)=0.0                                               CAS01540
C   --------------------- PRINT OUT HEADINGS                            CAS01550
      RSFJM=0.0                                                         CAS01560
       RSFJM1=0.0                                                       CAS01570
      JRSF=0                                                            CAS01580
      JRSF1=0                                                           CAS01590
      CALL OUTPH                                                        CAS01600
CHAPTER 2  2  2  2  2    GRID    2  2  2  2  2  2  2  2  2  2  2  2     CAS01610
C --------------------- QUANTITIES RELATED TO NX AND NY                 CAS01620
      CALL CONST2                                                       CAS01630
C-------------------------------------   CALCULATE GRID QUANTITIES      CAS01640
      CALL GEOM                                                         CAS01650
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      IF(KTEST.GT.0) CALL TEST 11                                       CAS01660
CHAPTER 3  3  3  3  3    VARIABLES    3  3  3  3  3  3  3  3  3  3  3   CAS01670
C--------------     SPECIFYING LIMITS OF J-RANGE FOR UPDATING JPHI'S    CAS01680
C                   ON WHICH VARIATIONS OF RHO AND EMU DEPEND           CAS01690
C     ---------------- RHO                                              CAS01700
      JLIM1=0                                                           CAS01710
      JLIM2=0                                                           CAS01720
C     ---------------- EMU                                              CAS01730
      JLIM3=JTKE                                                        CAS01740
      JLIM4=JTED                                                        CAS01750
C------------------------- CONSTANTS RELATED TO VARIABLES               CAS01760
      CALL CONST3                                                       CAS01770
      IF(KTEST.GT.0) CALL TEST 12                                       CAS01780
CHAPTER 4  4  4  4  4    PROPERTY DATA    4  4  4  4  4  4  4  4  4  4  CAS01790
C------------------------------ PUT REFERENCE VALUES IN FIELD           CAS01800
      DO 40 I=1,NXYG                                                    CAS01810
      RHO(I)=RHOREF                                                     CAS01820
40    EMU(I)=EMUREF                                                     CAS01830
C------------------------------ CELL-WALL DENSITY AND VISCOCITY         CAS01840
      DO 41 IY=1,NY                                                     CAS01850
      RHON(IY)=RHOREF                                                   CAS01860
      RHOS(IY)=RHOREF                                                   CAS01870
      RHOE(IY)=RHOREF                                                   CAS01880
      RHOW(IY)=RHOREF                                                   CAS01890
      EMUN(IY)=EMUREF                                                   CAS01900
      EMUS(IY)=EMUREF                                                   CAS01910
      EMUE(IY)=EMUREF                                                   CAS01920
41    EMUW(IY)=EMUREF                                                   CAS01930
CHAPTER 5  5  5  5  5    STARTING PREPARATIONS    5  5  5  5  5  5  5   CAS01940
C----- I INDICES FOR REFERENCE-PRESSURE POINT AND MONITORING LOCATION   CAS01950
      CALL CONST5                                                       CAS01960
C----------------------- CALCULATE FLOWIN AND REF. RES.-SOURCE VALUES   CAS01970
      FLOWIN=0.0                                                        CAS01980
      DO 530 IY=INLY1,INLY2                                             CAS01990
530   FLOWIN=FLOWIN+UINLET*RHOREF*DYV(IY)*R(IY)                         CAS02000
      RSREF(JPP)=FLOWIN                                                 CAS02010
      RSREF(JU)=FLOWIN*UINLET                                           CAS02020
      RSREF(JV)=RSREF(JU)                                               CAS02030
      RSREF(JH)=FLOWIN*HINLET                                           CAS02040
C VALUE OF TKE AND TED AT INLET                                         CAS02050
      TKEIN=FACTKE*UINLET**2                                            CAS02060
      TEDIN=TKEIN*SQRT(TKEIN)*CD/(FACTED*RLEG)                          CAS02070
C FACTORS FOR NORMALIZING RESIDUAL SOURCE                               CAS02080
      RSREF(JTKE)=TKEIN*FLOWIN                                          CAS02090
      RSREF(JTED)=TEDIN*FLOWIN                                          CAS02100
C CONSTANTS  FOR Y+                                                     CAS02110
      CYPTW=CD25*DYG(NY)/EMUREF                                         CAS02120
      CTAUTW=EMUREF/DYG(NY)                                             CAS02130
C  CONSTANTS FOR X+                                                     CAS02140
      CXPLW=CD25*DXG(2)/EMUREF                                          CAS02150
      CTAULW=EMUREF/DXG(2)                                              CAS02160
C------------------------------------ INITIALIZE VARIABLE STORAGES      CAS02170
      DO 50 JPHI=1,JLAST                                                CAS02180
      IF(JPHI.EQ.JRHO.OR.JPHI.EQ.JEMU) GO TO 50                         CAS02190
      I1=IZERO(JPHI)+1                                                  CAS02200
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      I2=ILAST(JPHI)                                                    CAS02210
      DO 51 I=I1,I2                                                     CAS02220
51    F(I)=0.0                                                          CAS02230
50    CONTINUE                                                          CAS02240
C---------------- PUT U=UINLET AND H=HINLET IN FIELD, EXCEPT AT WALL    CAS02250
      DO 5009 IX=2,NXM2                                                 CAS02260
      DO 5009 IY=2,NYM1                                                 CAS02270
      I=IY+NY*(IX-1)                                                    CAS02280
 5009 U(I)=1.0                                                          CAS02290
      DO 5010 IX=2,NXM1                                                 CAS02300
      DO 5010 IY=2,NYM2                                                 CAS02310
      I=IY+(IX-1)*NYM1                                                  CAS02320
 5010 V(I)=1.0                                                          CAS02330
      DO 5011 IX=1,NXM1                                                 CAS02340
      DO 5011 IY=2,NYM1                                                 CAS02350
      I=IY+(IX-1)*NY                                                    CAS02360
      TKE(I)=SQRT(TKEIN)                                                CAS02370
      TED(I)=SQRT(TEDIN)                                                CAS02380
      EMU(I)=CD*RHO(I)*TKE(I)**2/TED(I)+EMUREF                          CAS02390
 5011 CONTINUE                                                          CAS02400
      DO 5012 IY=INLY1,INLY2                                            CAS02410
      IX=2                                                              CAS02420
      I=IY+NY                                                           CAS02430
      IW=I-NY                                                           CAS02440
 5012 EMU(IW)=CD*RHO(IW)*TKEIN**2/TEDIN+EMUREF                          CAS02450
      DO 5013 IY=IOUT1,IOUT2                                            CAS02460
      I=IY+NY                                                           CAS02470
      IW=I-NY                                                           CAS02480
 5013 EMU(IW)=CD*RHO(IW)*TKEIN**2/TEDIN+EMUREF                          CAS02490
C-----------------INITIALIZE TDMA-LINE STORAGE                          CAS02500
      DO 555 IY=1,NXYP                                                  CAS02510
  555 P(IY)=0.0                                                         CAS02520
      DO 501 IY=1,NY                                                    CAS02530
      AN(IY)=0.0                                                        CAS02540
      DV(IY)=0.0                                                        CAS02550
      AS(IY)=0.0                                                        CAS02560
      AE(IY)=0.0                                                        CAS02570
      AW(IY)=0.0                                                        CAS02580
      SU(IY)=0.0                                                        CAS02590
      SP(IY)=0.0                                                        CAS02600
      DU(IY)=0.0                                                        CAS02610
      VOLUME(IY)=0.0                                                    CAS02620
      PP(IY)=0.0                                                        CAS02630
501   PHIOLD(IY)=0.0                                                    CAS02640
C_______________INITIALIZE Y-DIRECTION ARRAYS                           CAS02650
      DO 502 IX=1,NX                                                    CAS02660
      YPUST1(IX)=0.0                                                    CAS02670
      YPUST2(IX)=0.0                                                    CAS02680
      TAUTW1(IX)=0.0                                                    CAS02690
  502 TAUTW2(IX)=0.0                                                    CAS02700
C--------------INITIALIZE Y-DIRECTION ARRAYS                            CAS02710
      DO 503 IY=1,NY                                                    CAS02720
      TAULW(IY)=0.0                                                     CAS02730
  503 XPUSLW(IY)=0.0                                                    CAS02740
C---------------------------------- PRINT OUT STARTING VALUES           CAS02750
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      IF(KTEST.GT.0) CALL TEST 13                                       CAS02760
      IF(KINPRI.GT.0) CALL OUTPF                                        CAS02770
      GO TO 60                                                          CAS02780
55    IF(ISTEP.GT.1) GO TO 65                                           CAS02790
CHAPTER 6  6  6  6  6    STEP CONTROL    6  6  6  6  6  6  6  6  6  6   CAS02800
60    CONTINUE                                                          CAS02810
      DO 69 JPHI=1,NEQ                                                  CAS02820
69    RSSUM(JPHI)=0.0                                                   CAS02830
      RSSUM(JPP)=0.0                                                    CAS02840
      FLOWUP=FLOWIN                                                     CAS02850
      IF(ISTEP.GT.1) GO TO 64                                           CAS02860
      IF(ILINE.GT.0) GO TO 65                                           CAS02870
C---------------- Y-DIRECTION TDMA TRAVERSES                            CAS02880
62    LINEF=2                                                           CAS02890
      LINEL=NXM1                                                        CAS02900
      NODEF=2                                                           CAS02910
      NODEL=NYM1                                                        CAS02920
C---------------------- FOR BOTH X- AND Y-DIRECTION TRAVERSES           CAS02930
      NODEF1=NODEF-1                                                    CAS02940
      NODEL1=NODEL-1                                                    CAS02950
      NODLP1=NODEL+1                                                    CAS02960
64    ILINE=LINEF                                                       CAS02970
C---------------------- QUANTITIES RELATED TO IX VALUE OF TDMA LINE     CAS02980
65    CONTINUE                                                          CAS02990
      IX=ILINE                                                          CAS03000
      IXP1=IX+1                                                         CAS03010
      IX1NY=(IX-1)*NY                                                   CAS03020
      IX1NY1=(IX-1)*NYM1                                                CAS03030
      IX2NY2=(IX-2)*NYM2                                                CAS03040
      DO 66 JPHI=1,JLAST                                                CAS03050
66    IXNY(JPHI)=IX1NY                                                  CAS03060
      IXNY(JV)=IX1NY1                                                   CAS03070
      IXNY(JP)=IX2NY2-1                                                 CAS03080
CHAPTER 7  7  7  7  7    BOUNDARY CONDITIONS    7  7  7  7  7  7  7  7  CAS03090
      IF(ISTEP.LT.ISTCH) GO TO 70                                       CAS03100
      RELAX(JTKE)=RELTKE                                                CAS03110
      RELAX(JTED)=RELTED                                                CAS03120
70    CONTINUE                                                          CAS03130
      IF(ISTEP.GT.1) GO TO 799                                          CAS03140
C ---------U V H ON THE LADLE WALL                                      CAS03150
         IN=NY+IX1NY                                                    CAS03160
      INV=NY-1+IX1NY1                                                   CAS03170
      IS=1+IX1NY                                                        CAS03180
      ISV=1+IX1NY1                                                      CAS03190
      U(IN)=0.0                                                         CAS03200
      V(INV)=0.0                                                        CAS03210
      U(IS)=0.0                                                         CAS03220
      V(ISV)=0.0                                                        CAS03230
      IF(IX.NE.2) GO TO 75                                              CAS03240
      DO 7001 I=1,I1M1                                                  CAS03250
 7001 U(I)=0.0                                                          CAS03260
      DO 7002 I=INLY1,INLY2                                             CAS03270
      TKE(I)=TKEIN                                                      CAS03280
      TED(I)=TEDIN                                                      CAS03290
 7002 U(I)=UINLET                                                       CAS03300
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      DO 7003 I=I2P1,I3M1                                               CAS03310
 7003 U(I)=0.0                                                          CAS03320
      DO 7004 I=IOUT1,IOUT2                                             CAS03330
      TKE(I)=TKEIN                                                      CAS03340
      TED(I)=TEDIN                                                      CAS03350
 7004 U(I)=-UINLET                                                      CAS03360
      DO 7005 I=I4P1,NY                                                 CAS03370
 7005 U(I)=0.0                                                          CAS03380
   75 CONTINUE                                                          CAS03390
  799 CONTINUE                                                          CAS03400
C-------CALCULATE TAU AND Y+ FOR LADLE WALL LEFT                         CAS03410
      I=2+IX1NY                                                         CAS03420
      IE=I-NY                                                           CAS03430
      UP=U(IE)+(U(I)-U(IE))*FUNODE(IX)                                  CAS03440
      ABSUP=ABS(UP)                                                     CAS03450
      IF(IX.EQ.2.AND.ABSUP.LE.TINY) UP=TINY                             CAS03460
      RSQRTK=RHO(I)*SQRT(TKE(I))                                        CAS03470
      YPUST1(IX)=RSQRTK*CYPTW                                           CAS03480
      IF(YPUST1(IX).GT.11.5) GO TO 701                                  CAS03490
      TAUTW1(IX)=CTAUTW*UP                                              CAS03500
      GO TO 710                                                         CAS03510
  701 TAUTW1(IX)=CAPPA*UP*RSQRTK*CD25/ALOG(ECONST*YPUST1(IX))            CAS03520
  710 CONTINUE                                                          CAS03530
C---------CALCULATE TAU AND Y+ FORLADLE WALL- RIGHT                     CAS03540
      I=NYM1+IX1NY                                                      CAS03550
      IW=I-NY                                                           CAS03560
      UP=U(IW)+(U(I)-U(IW))*FUNODE(IX)                                  CAS03570
      ABSUP=ABS(UP)                                                     CAS03580
      IF(IX.EQ.2.AND.ABSUP.LE.TINY) UP=TINY                             CAS03590
       RSQRTK=RHO(I)*SQRT(TKE(I))                                       CAS03600
      YPUST2(IX)=RSQRTK*CYPTW                                           CAS03610
      IF(YPUST2(IX).GT.11.5) GO TO 702                                  CAS03620
      TAUTW2(IX)=CTAUTW-UP                                              CAS03630
      GO TO 711                                                         CAS03640
  702 TAUTW2(IX)=CAPPA*UP*RSQRTK*CD25/ALOG(ECONST*YPUST2(IX))            CAS03650
  711 CONTINUE                                                          CAS03660
C  CALCULATE TAU AND X+ FOR LADLE BOTTOM                                CAS03670
      IF(IX.NE.NXM1) GO TO 720                                          CAS03680
      DO 721 IY=2,NYM1                                                  CAS03690
      I=IY+IX1NY                                                        CAS03700
      IV=IY+IX1NY1                                                      CAS03710
      ISV=IV-1                                                          CAS03720
      VP=V(ISV)+(V(IV)-V(ISV))*FVNODE(IY)                               CAS03730
      RSQRTK=RHO(I)*SQRT(TKE(I))                                        CAS03740
      XPUSLW(IY)=RSQRTK*CXPLW                                           CAS03750
      IF(XPUSLW(IY).GT.11.5) GO TO 722                                  CAS03760
      TAULW(IY)=CTAULW*VP                                               CAS03770
      GO TO 721                                                         CAS03780
  722 TAULW(IY)=CAPPA*VP*RSQRTK*CD25/ALOG(ECONST*XPUSLW(IY))             CAS03790
  721 CONTINUE                                                          CAS03800
  720 CONTINUE                                                          CAS03810
CHAPTER 8  8  8  8  8    ADVANCE    8  8  8  8  8  8  8  8  8  8  8  8  CAS03820
80    CONTINUE                                                          CAS03830
C---------------- PUT NTRAVS EQUAL TO NTDMA,OR TO OTHER VALUES TO GIVE  CAS03840
C                    MULTI-TRAVERSE ON SELECTED LINES                   CAS03850
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      NTRAVS=NTDMA                                                      CAS03860
C---------------------- PUT GREAT INTO ARSL'S                           CAS03870
      DO 85 J=1,NEQ                                                     CAS03880
85    ARSL(IX,J)=GREAT                                                  CAS03890
C - OUTER LOOP FOR CARRYING OUT A MAX. OF NTRAVS TRAVERSES ON LINE IX    CAS03900
      DO 1000 NT=1,NTRAVS                                               CAS03910
      KOUNT(IX)=NT                                                      CAS03920
      RSMAX=0.                                                          CAS03930
C - INNER LOOP FOR ALL VARIABLES (PLUS ONE FOR PREPARATIONS FOR TRANSFERCAS03940
C   TO NEXT LINE OR TO NEXT SWEEP OF FIELD)                             CAS03950
      DO 1001 JPHI=1,NEQP1                                              CAS03960
      IF(JPHI.EQ.NEQP1) GO TO 960                                       CAS03970
      IF(KSOLVE(JPHI).EQ.0) GO TO 1001                                  CAS03980
      JG=JGROUP(JPHI)                                                   CAS03990
      IF(JG.NE.5) GO TO 84                                              CAS04000
      IF(NT.EQ.NTRAVS) GO TO 81                                         CAS04010
      IF(RSMAX.GT.RSCHEK) GO TO 1001                                    CAS04020
84    IF(ARSL(IX,JPHI).LT.RSCHEK.AND.ARSL(IX,JPHI).GT.0.) GO TO 1001    CAS04030
81    IF(JPHI.NE.JU) GO TO 83                                           CAS04040
      IF(IX.EQ.NXM1) GO TO 1001                                         CAS04050
C---------------------- UPDATE JPHI ON TDMA LINE                        CAS04060
83    RSLINE(IX,JPHI)=0.0                                               CAS04070
      LABPHI=JPHI                                                       CAS04080
      CALL COEFF(JPHI)                                                  CAS04090
      CALL MODIFY(JPHI)                                                 CAS04100
      IF(KTEST.GT.2) CALL TEST 31                                       CAS04110
      CALL SOLVE(JPHI)                                                  CAS04120
      IF(JPHI.GE.JU) CALL BOUND(JPHI)                                   CAS04130
      RSLINE(IX,JPHI)=RSLINE(IX,JPHI)/RSREF(JPHI)                       CAS04140
      ABSRS=ABS(RSLINE(IX,JPHI))                                        CAS04150
      ARSL(IX,JPHI)=ABSRS                                               CAS04160
      RSMAX=AMAX1(RSMAX,ABSRS)                                          CAS04170
      IF(KTEST.GT.1) CALL TEST 21                                       CAS04180
      GO TO (1010,1020,930,940,1001), JG                                CAS04190
CHAPTER 9  9  9  9  9    COMPLETE    9  9  9  9  9  9  9  9  9  9  9  9 CAS04200
930   CONTINUE                                                          CAS04210
COMMENT  INSERT INSTRUCTIONS HERE TO UPDATE RHO. ALSO CALL              CAS04220
COMMENT  BOUND(RHO) IF APPROPRIATE                                      CAS04230
      GO TO 1011                                                        CAS04240
940   CONTINUE                                                          CAS04250
COMMENT  INSERT INSTRUCTIONS HERE TO UPDATE EMU. ALSO CALL              CAS04260
COMMENT  BOUND(EMU) IF APPROPRIATE                                      CAS04270
      DO 911 IY=NODEF,NODEL                                             CAS04280
      I=IY+IX1NY                                                        CAS04290
      EMUNEW=(CD*RHO(I)*TKE(I)/(TED(I)+TINY))*TKE(I)+EMUREF             CAS04300
      EMU(I)=EMU(I)+(EMUNEW-EMU(I))*RELAX(JEMU)                         CAS04310
  911 CONTINUE                                                          CAS04320
      CALL BOUND(JEMU)                                                  CAS04330
      GO TO 1001                                                        CAS04340
960   IF(NT.EQ.NTRAVS) GO TO 961                                        CAS04350
      IF(RSMAX.LE.RSCHEK) GO TO 961                                     CAS04360
      GO TO 1001                                                        CAS04370
C-------------    PREPARATIONS FOR TRANSFER TO THE NEXT LINE OR TO      CAS04380
C                 THE NEXT SWEEP OF THE FIELD                           CAS04390
C     ------------ SUM OF RESIDUAL-SOURSE VALUES ON LINE FOR EACH JPHI  CAS04400
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961   DO 962 J=1,JPP                                                    CAS04410
      IF(KSOLVE(J).EQ.0) GO TO 962                                      CAS04420
      IF(J.EQ.JU.AND.IX.EQ.NXM1) GO TO 962                              CAS04430
      RSSUM(J)=RSSUM(J)+ARSL(IX,J)                                      CAS04440
962   CONTINUE                                                          CAS04450
C---------------------- CHECK IF LAST LINE OF FIELD REACHED            CAS04460
      IF(ILINE.EQ.LINEL) GO TO 963                                      CAS04470
C---------------------- PREPARE  FOR MOVING TO NEXT LINE                CAS04480
COMMENT  IF REQUIRED, CALCULATE FLOWUP FOR THE NEW LINE HERE. IN THE    CAS04490
COMMENT  PRESENT SET-UP FLOWUP HAS BEEN PUT EQUAL TO FLOWIN, AS         CAS04500
COMMENT  PROBLEMS OF THE FIXED FLOW-RATE TYPE ASSUMED                   CAS04510
      ILINE=ILINE+1                                                     CAS04520
      GO TO 55                                                          CAS04530
C - PREPARE FOR BEGINNING THE NEXT SWEEP OF THE FIELD                   CAS04540
C            MAX. RESIDUAL-SOURCE VALUE IN FIELD FOR CONVERGENCE CHECK  CAS04550
963   RSMAX=0.0                                                         CAS04560
      DO 964 J=1,JPP                                                    CAS04570
964   RSMAX=AMAX1(RSMAX,RSSUM(J))                                       CAS04580
C                      ADJUST P'S TO GIVE ZERO AT REF. LOCATION         CAS04590
      PIPREF=P(IPREF)                                                   CAS04600
      DO 965 IP=1,NXYP                                                  CAS04610
  965 P(IP)=P(IP)-PIPREF                                                CAS04620
      GO TO 110                                                         CAS04630
CHAPTER 10  10  10  10    ADJUST    10  10  10  10  10  10  10  10      CAS04640
C----------------------- ADJUSTMENT AFTER UPDATING U'S                  CAS04650
1010  IF(KSOLVE(JRHO).EQ.0) GO TO 1011                                  CAS04660
      CALL BOUND(JU)                                                    CAS04670
      GO TO 1001                                                        CAS04680
C---------------------- OVERALL CONTINUITY CORRECTION                   CAS04690
1011  IF(KMPA.NE.0) CALL OVACON                                         CAS04700
      CALL BOUND(JU)                                                    CAS04710
      IF(KTEST.GT.1) CALL TEST 22                                       CAS04720
      GO TO 1001                                                        CAS04730
C---------------------- ADJUSTMENT AFTER UPDATING V'S                   CAS04740
1020  IF(KSOLVE(JPP).NE.0) GO TO 1021                                   CAS04750
      CALL BOUND(JV)                                                    CAS04760
      GO TO 1001                                                        CAS04770
C---------------------- CELL-WISE CONTINUITY CORRECTION                 CAS04780
1021  RSLINE(IX,JPP)=0.0                                                CAS04790
      CALL COEFF(JPP)                                                   CAS04800
      CALL MODIFY(JPP)                                                  CAS04810
      LABPHI=JPP                                                        CAS04820
      IF(KTEST.GT.2) CALL TEST 31                                       CAS04830
      CALL SOLVE(JPP)                                                   CAS04840
      RSLINE(IX,JPP)=RSLINE(IX,JPP)/RSREF(JPP)                          CAS04850
      ARSL(IX,JPP)=ABS(RSLINE(IX,JPP))                                  CAS04860
      CALL CELCON                                                       CAS04870
      IF(KTEST.GT.1) CALL TEST 23                                       CAS04880
      CALL BOUND(JV)                                                    CAS04890
      GO TO 1001                                                        CAS04900
C---------------------- END OF INNER J-LOOP                             CAS04910
1001  CONTINUE                                                          CAS04920
C---------------------- END OF OUTER NTRAVS LOOP                        CAS04930
1000  CONTINUE                                                          CAS04940
CHAPTER 11  11  11  11    PRINT    11  11  11  11  11  11  11  11  11   CAS04950
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110   CONTINUE                                                          CAS04960
C----------------------- PRINT OUT RESIDUAL SOURCES AND VARIABLE VALUES CAS04970
C                        AT MONITORING LOCATION (IXMON,IYMON)           CAS04980
      IF(MOD(ISTEP,NOUTP1).EQ.0) CALL OUTP1                             CAS04990
C----------------------- PRINT OUT OF FIELD VALUES                      CAS05000
      IF(RSMAX.LE.CCHECK) GO TO 115                                     CAS05010
      IF(ISTEP.LT.0) GO TO 115                                          CAS05020
114   IF(MOD(ISTEP,IPRINT).NE.0.OR.ISTEP.EQ.0) GO TO 112                CAS05030
115   CALL OUTPF                                                        CAS05040
      GO TO 120                                                         CAS05050
112   IF(ISTEP.EQ.LASTEP) CALL OUTPF                                    CAS05060
CHAPTER 12  12  12  12   DECIDE    12  12  12  12  12  12  12  12  12   CAS05070
C----------------------- CONVERGENCE CHECK                              CAS05080
120   IF(RSMAX.LE.CCHECK) GO TO 1299                                    CAS05090
C----------------------- CHECK IF LAST STEP IS REACHED                  CAS05100
      IF(ISTEP.GE.LASTEP) GO TO 129                                     CAS05110
128   ISTEP=ISTEP+1                                                     CAS05120
      GO TO 60                                                          CAS05130
129   CALL OUTP2                                                        CAS05140
 1299 WRITE(9,1300) NX ,NY                                              CAS05150
      WRITE(9,1301) (X(I),I=1,NX)                                       CAS05160
      WRITE(9,1301) (Y(I),I=1,NY)                                       CAS05170
      WRITE(9,1301) (F(I),I=1,3766)                                     CAS05180
 1300 FORMAT(2I4)                                                       CAS05190
 1301 FORMAT(5E13.5)                                                    CAS05200
      END                                                               CAS05210
      SUBROUTINE OUTPUT                                                 CAS05220
      COMMON                                                            CAS05230
     1/CASE1/UINLET,FLOWIN,RPIPE,XPIPE,FXSTEP,HINLET,HWALL              CAS05240
     2/DNY/ DYG(22),DYV(22),FV(22),FVNODE(22),R(22),RDYG(22),RDYV(22)   CAS05250
     2,RSYG(22),RSYV(22),RV(22),RVCB(22),SYG(22),SYV(22),Y(22),YV(22)   CAS05260
     3/DNYONX/AE(22),AN(22),AP(22),AS(22),AW(22),C(22),D(22),DIFE(22)   CAS05270
     3,DIFN(22),DUW(22), DIFW(22),DU(22),DV(22),EMUE(22),EMUN(22)       CAS05280
     3         ,EMUW(22),HCONE(22),HCONN(22),           HCONW(22)       CAS05290
     3,PHIOLD(22),RHOE(22),RHON(22),         RHOW(22),SP(22),SU(22)     CAS05300
     3,VOLUME(22),CONN(22),CONS(22),CONE(22),CONW(22),ESMPHI(22)        CAS05310
     4/DNX/ DXG(22),DXU(22),FU(22),FUNODE(22),KOUNT(22),RDXG(22)        CAS05320
     4,RDXU(22),RSXG(22),RSXU(22),STORE(22),SXG(22),SXU(22),X(22),XU(22)CAS05330
     5/DJPHI/ IEW(10),ILAST(10),IMON(10),IXNY(10),IZERO(10)             CAS05340
     5,JGROUP(10),KADSOR(10),KSOLVE(10),KRS(10),RELAX(10),RSREF(10)     CAS05350
     5,RSSUM(10),ITITLE(10)                                             CAS05360
      COMMON                                                            CAS05370
     6/DO/CCHECK,DP,FLOWPC,FLOWST,FLOWUP,GREAT,ILINE,IPLRS,IPREF,IPRINT CAS05380
     6,ISTEP ,IX,IX1NY,IX1NY1,IX2NY2,IXMON,IXP1,IXPREF,IYMON,IYPREF     CAS05390
     6,JEMU,JH,JLAST,JLIM1,JLIM2,JLIM3,JLIM4,JP,JPP,JRHO                CAS05400
     6,JU,JV,JVP1,KINPRI,KMPA,KRAD,KRHOMU,KTEST,LABPHI                  CAS05410
     6,LASTEP,LINEF,LINEL,NEQ,NEQP1                                     CAS05420
     6,NODEF,NODEF1,NODEL,NODEL1,NODLP1,NTDMA,NUMCOL                    CAS05430
     6,NX,NXMAX,NXM1,NXM2,NXYG,NXYP,NXYU,NXYV                           CAS05440
     6,NY,NYMAX,NYM1,NYM2,PI,RSCHEK,RSMAX,TINY                          CAS05450
      COMMON/PROP/EMUREF,PRL(10),PRT(10),RHOREF                         CAS05460
      COMMON/D2D1/ARSL(22,10),RSLINE(22,10)                             CAS05470
      COMMON/D2D2/U(462),V(462),TKE(484),TED(484),H(484),PP(22),P(400)  CAS05480
     7, RHO(484),EMU(484)                                               CAS05490
     7, INLY(10),IOUT(10),KIN,KOUT,RELTKE,RELTED,ISTCH                  CAS05500
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      COMMON                                                            CAS05510
     9/TURB/C1,C2,CD,SQRTCD,CD25,ECONST,CTAUTW,CYPTW,TAUTW1(22)         CAS05520
     9,TAUTW2(22),YPUST1(22),YPUST2(22)                                 CAS05530
     9,TAULW(22),XPUSLW(22),CTAULW,CXPLW                                CAS05540
     9,GENK(22),FACTKE,FACTED,JTKE,JTED,CAPPA                           CAS05550
     9,INLY1,INLY2,IOUT1,IOUT2,I1M1,I2P1,I3M1,I4P1                      CAS05560
      COMMON/ABC/AREAE                                                  CAS05570
      DIMENSION F(3766)                                                 CAS05580
      DIMENSION DIFS(22),EMUS(22),HCONS(22),RHOS(22)                    CAS05590
      EQUIVALENCE (DIFS(2),DIFN(1)), (EMUS(2),EMUN(1))                  CAS05600
      EQUIVALENCE (RHOS(2),RHON(1)), (AREAE,AREAW)                      CAS05610
      EQUIVALENCE (HCONS(2),HCONN(1))                                   CAS05620
      EQUIVALENCE (F(1),U(1))                                           CAS05630
      DIMENSION A(22),B(22)                                             CAS05640
      EQUIVALENCE(A(1),AN(1)),(B(1),AS(1))                              CAS05650
      DATA KTRIP/0/                                                     CAS05660
CHAPTER 1  1  1  1  1  PRELIMINARIES  1  1  1  1  1  1  1  1  1  1  1   CAS05670
CHAPTER 2  2  2  2     HEADINGS    2  2  2  2  2  2  2  2  2  2  2  2   CAS05680
      ENTRY OUTPH                                                       CAS05690
C------------------------------      THE PROBLEM                        CAS05700
20    WRITE(6,201)                                                      CAS05710
201   FORMAT(///1X,10X,50HLAMINAR,UNIFORM-PROPERTY FLOW IN A CIRCULAR PICAS05720
     1PE  /1X,10X,50(1H-))                                              CAS05730
C-----------------------------------     PROBLEM INFORMATION            CAS05740
      REY=RHOREF*UINLET*2.*RPIPE/EMUREF                                 CAS05750
      WRITE(6,210) XPIPE,RPIPE,UINLET,REY,HINLET,HWALL                  CAS05760
210   FORMAT(//1X,10H     XPIPE,10H     RPIPE,10H    UINLET,            CAS05770
     110H  REY. NO.,10H    HINLET,10H     HWALL/1X,1P6E10.2)            CAS05780
      WRITE(6,250) NX,NY,NXMAX,NYMAX                                    CAS05790
      WRITE(6,251) KRAD,NTDMA,KMPA,LASTEP,RSCHEK,CCHECK                 CAS05800
250   FORMAT(/1X,10H        NX,10H        NY,10H     NXMAX,10H     NYMAXCAS05810
     1/1X,4I10)                                                         CAS05820
251   FORMAT(/1X,10H      KRAD,10H     NTDMA,10H      KMPA,10H    LASTEPCAS05830
     1,10H    RSCHEK,10H    CCHECK/1X,4I10,1P2E10.2)                    CAS05840
      RETURN                                                            CAS05850
CHAPTER 3  3  3  3  3  FIELD VALUES   3  3  3  3  3  3  3  3  3  3  3   CAS05860
      ENTRY OUTPF                                                       CAS05870
      DO 31 JPHI=1,JLAST                                                CAS05880
      IF(JPHI.EQ.JPP) GO TO 31                                          CAS05890
      IF(KSOLVE(JPHI).EQ.0) GO TO 31                                    CAS05900
32    CALL PRINT(JPHI)                                                  CAS05910
31    CONTINUE                                                          CAS05920
      KTRIP=0                                                           CAS05930
      RETURN                                                            CAS05940
CHAPTER 4  4  4  4  PRINT OUT OF RESIDUAL SOURCES AND MONITORING VALUES CAS05950
      ENTRY OUTP1                                                       CAS05960
      IF(ISTEP.LE.2) GO TO 110                                          CAS05970
      IF(MOD(ISTEP,IPLRS).NE.0) GO TO 1140                              CAS05980
110   WRITE(6,1100) ISTEP,ISTEP                                         CAS05990
      WRITE(6,9999)                                                     CAS06000
      WRITE(6,1101) (ITITLE(K),K=1,JP)                                  CAS06010
      DO 118 IX=2,NXM1                                                  CAS06020
118   WRITE(6,1102) IX,KOUNT(IX),(RSLINE(IX,J),J=1,JPP)                 CAS06030
1150  WRITE(6,1103) (RSSUM(J),J=1,JPP)                                  CAS06040
      DO 116 J=1,JP                                                     CAS06050
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      IF(J.NE.JPP) GO TO 1160                                           CAS06060
      STORE(J)=0.0                                                      CAS06070
      GO TO 116                                                         CAS06080
1160  I=IMON(J)+IZERO(J)                                                CAS06090
      STORE(J)=F(I)                                                     CAS06100
116   CONTINUE                                                          CAS06110
      WRITE(6,1104) IXMON,IYMON                                         CAS06120
      WRITE(6,1105) (STORE(J),J=1,JP)                                   CAS06130
      KTRIP=0                                                           CAS06140
C---------------------- KTRIP IS A LOCAL 'TRIPPING CONTROL SWITCH'      CAS06150
      GO TO 1170                                                        CAS06160
1140  KTRIP=KTRIP+1                                                     CAS06170
      IF(KTRIP.GT.1) GO TO 1141                                         CAS06180
      WRITE(6,1114)                                                     CAS06190
      WRITE(6,1110) IXMON,IYMON                                         CAS06200
      WRITE(6,9999)                                                     CAS06210
      WRITE(6,1111) (ITITLE(K),K=1,JP)                                  CAS06220
1141  WRITE(6,1112) ISTEP,(RSSUM(J),J=1,JPP)                            CAS06230
      DO 117 J=1,JP                                                     CAS06240
      IF(J.NE.JPP) GO TO 1142                                           CAS06250
      STORE(J)=0.0                                                      CAS06260
      GO TO 117                                                         CAS06270
1142  I=IMON(J)+IZERO(J)                                                CAS06280
      STORE(J)=F(I)                                                     CAS06290
117   CONTINUE                                                          CAS06300
      WRITE(6,1113) ISTEP,(STORE(J),J=1,JP)                             CAS06310
1170  CONTINUE                                                          CAS06320
1100  FORMAT(/1X,14HITERATION NO. ,I3,2X,70(1H=),4X,14HITERATION NO. ,  CAS06330
     1      I3//                                                        CAS06340
     1  1X,63HALGEBRAIC SUM OF RESIDUAL SOURCES AT EACH LINE--RSLINE(IX,CAS06350
     1JPHI)/)                                                           CAS06360
1101  FORMAT(1X,13HIX  NO. TRAVS,2X,10(3X,I4,3X))                       CAS06370
1102  FORMAT(1X,I2,6X,I2,3X,1P10E10.2)                                  CAS06380
1103  FORMAT(/1X,37HSUM OF ABS. VALUES OF RSLINE(IX,JPHI)//             CAS06390
     11X,13(1H-),1P10E10.2/)                                            CAS06400
1104  FORMAT(/1X,31HVALUES AT MONITORING LOCATION (,I2,1H,,I2,1H)/      CAS06410
     1    1X,6X,1P10E10.2)                                              CAS06420
1105  FORMAT(1X,13(1H-),1P10E10.2)                                      CAS06430
1110  FORMAT(/1X,58HSUM OF ABS. VALUES OF RSLINE(IX,JPHI), PRECEDED BY  CAS06440
     1******/1X,30HVALUES AT MONITORING LOCATION(,I2,1H,,I2,1H),        CAS06450
     2  22H,  PRECEDED BY  ------)                                      CAS06460
1111  FORMAT(/1X,6X,5HITER.,3X,10(3X,I4,3X))                            CAS06470
1112  FORMAT(/1X,6H-*****,1X,I3,3X,1P10E10.2)                           CAS06480
1113  FORMAT(1X,6H------,1X,I3,3X,1P10E10.2)                            CAS06490
1114  FORMAT(//1X,60(1H-))                                              CAS06500
9999  FORMAT(/1X,56H( 1 = U, 2 = V, 3 = H, 4 = PP, 5 = P, 6 = RHO, 7 = ECAS06510
     1MU )/)                                                            CAS06520
      RETURN                                                            CAS06530
CHPTER 5 5 5 5 5 5 5                                                    CAS06540
      ENTRY OUTP2                                                       CAS06550
      DO50 IX=2,NXM1                                                    CAS06560
      I=2+(IX-1)*NY                                                     CAS06570
   50 STORE(IX)=TKE(I)/ABS(TAUTW1(IX)/RHO(I))                           CAS06580
      WRITE(6,500) (IX,TAUTW1(IX),YPUST1(IX),STORE(IX),IX=2,NXM1)       CAS06590
  500 FORMAT(//1X,20H VALUES OF      WALL//1X,3H IX,2X,11H TUU       ,  CAS06600
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    111H    Y+       ,11H K/UTAU**2 /(1X,I3,2X,1P3E11.3))                CAS06610
      DO 59 IX=2,NXM1                                                    CAS06620
      I=NXM1+(IX-1)*NY                                                   CAS06630
   59 STORE(IX)=TKE(I)/ABS(TAUTW2(IX)/RHO(I))                            CAS06640
      WRITE(6,500) (IX,TAUTW2(IX),YPUST2(IX),STORE(IX),IX=2,NXM1)        CAS06650
      FACTOR=CD/CD25                                                     CAS06660
C----------CALAULATE AND PRINT OUT LENGTH SCALE                           CAS06670
      DO 503 IX=1,NX                                                     CAS06680
      DO 503 IY=1,NY                                                     CAS06690
      I=IY+(IX-1)*NY                                                     CAS06700
  503 TED(I)=FACTOR*TKE(I)*SQRT(TKE(I))/(TKE(I)*RPIPE+TINY)              CAS06710
      CALL PRINT(JTED)                                                   CAS06720
      RETURN                                                             CAS06730
      END                                                                CAS06740
      SUBROUTINE CONST                                                   CAS06750
      COMMON                                                             CAS06760
     1/CASE1/UINLET,FLOWIN,RPIPE.XPIPE,FXSTEP,HINLET,HWALL               CAS06770
     2/DNY/ DYG(22),DYV(22),FV(22),FVNODE(22),R(22),RDYG(22),RDYV(22)    CAS06780
     2,RSYG(22),RSYV(22),RV(22),RVCB(22),SYG(22),SYV(22),Y(22),YV(22)    CAS06790
     3/DNYONX/AE(22),AN(22),AP(22),AS(22),AW(22),C(22),D(22),DIFE(22)    CAS06800
     3,DIFN(22),DUW(22), DIFW(22),DU(22),DV(22),EMUE(22),EMUN(22)        CAS06810
     3         ,EMUW(22),HCONE(22),HCONN(22),          HCONW(22)         CAS06820
     3,PHIOLD(22),RHOE(22),RHON(22),          RHOW(22),SP(22),SU(22)     CAS06830
     3,VOLUME(22),CONN(22),CONS(22),CONE(22),CONW(22),ESMPHI(22)         CAS06840
     4/DNX/ DXG(22),DXU(22),FU(22),FUNODE(22),KOUNT(22),RDXG(22)         CAS06850
     4,RDXU(22),RSXG(22),RSXU(22),STORE(22),SXG(22),SXU(22),X(22),XU(22)CAS06860
     5/DJPHI/ IEW(10),ILAST(10),IMON(10),IXNY(10),IZERO(10)              CAS06870
     5,JGROUP(10),KADSOR(10),KSOLVE(10),KRS(10),RELAX(10),RSREF(10)      CAS06880
     5,RSSUM(10),ITITLE(10)                                              CAS06890
      COMMON                                                             CAS06900
     6/DO/CCHECK.DP,FLOWPC,FLOWST,FLOWUP,GREAT,ILINE,IPLRS,I[illegible]EF,IPRINT CAS06910
     6,ISTEP  ,IX,IX1NY.IX1NY1,IX2NY2,IXMON,IXP1,IXPREF,IYMON   /PREF    CAS06920
     6,JEMU,JH,JLAST,JLIM1,JLIM2,JLIM3,JLIM4,JP,JPP,JRHO                 CAS06930
     6,JU,JV,JVP1,KINPRI,KMPA,KRAD,KRHOMU,KTEST,LABPHI                   CAS06940
     6,LASTEP,LINEF,LINEL,NEQ,NEQP1                                      CAS06950
     6,NODEF,NODEF1,NODEL,NODEL1,NODLP1,NTDMA,NUMCOL                     CAS06960
     6,NX,NXMAX,NXM1,NXM2,NXYG,NXYP,NXYU,NXYV                            CAS06970
     6,NY,NYMAX,NYM1,NYM2,PI,RSCHEK,RSMAX,TINY                           CAS06980
      COMMON/PROP/EMUREF,PRL(10),PRT(10),RHOREF                          CAS06990
      COMMON/D2D1/ARSL(22,10),RSLINE(22,10)                              CAS07000
      COMMON/D2D2/U(462),V(462),TKE(484),TED(484),H(484),PP(22),P(400)   CAS07010
     7,RHO(484),EMU(484)                                                 CAS07020
     7,INLY(10),IOUT(10),KIN,KOUT,RELTKE,RELTED,ISTCH                    CAS07030
      COMMON                                                             CAS07040
     9/TURB/C1,C2,CD,SQRTCD,CD25,ECONST,CTAUTW,CYPTW,TAUTW1(22)          CAS07050
     9,TAUTW2(22),YPUST1(22),YPUST2(22)                                  CAS07060
     9,TAULW(22),XPUSLW(22),CTAULW,CXPLW                                 CAS07070
     9,GENK(22),FACTKE,FACTED,JTKE,JTED,CAPPA                            CAS07080
     9,INLY1,INLY2,IOUT1,IOUT2,I1M1,I2P1,I3M1,I4P1                       CAS07090
      COMMON/ABC/AREAE                                                   CAS07100
      DIMENSION F(3766)                                                  CAS07110
      DIMENSION DIFS(22),EMUS(22),HCONS(22),RHOS(22)                     CAS07120
      EQUIVALENCE (DIFS(2),DIFN(1)), (EMUS(2),EMUN(1))                   CAS07130
      EQUIVALENCE (RHOS(2),RHON(1)), (AREAE,AREAW)                       CAS07140
      EQUIVALENCE (HCONS(2),HCONN(1))                                    CAS07150
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      EQUIVALENCE (F(1),U(1))                                           CAS07160
      DIMENSION A(22),B(22)                                             CAS07170
      EQUIVALENCE(A(1),AN(1)),(B(1),AS(1))                              CAS07180
C-------------------- CONSTANTS RELATED TO NX AND NY -----------------CAS07190
      ENTRY CONST2                                                      CAS07200
      NXM1=NX-1                                                         CAS07210
      NXM2=NX-2                                                         CAS07220
      NYM1=NY-1                                                         CAS07230
      NYM2=NY-2                                                         CAS07240
C --------------------- TOTAL NUMBER OF NODES FOR DIFFERENT VARIABLES  CAS07250
      NXYG=NX*NY                                                        CAS07260
      NXYP=NXM2*NYM2                                                    CAS07270
      NXYU=NXM1*NY                                                      CAS07280
      NXYV=NX*NYM1                                                      CAS07290
      INLY1=INLY(1)                                                     CAS07300
      INLY2=INLY(KIN)                                                   CAS07310
      IOUT1=IOUT(1)                                                     CAS07320
      IOUT2=IOUT(KOUT)                                                  CAS07330
      I1M1=INLY1-1                                                      CAS07340
      I2P1=INLY2+1                                                      CAS07350
      I3M1=IOUT1-1                                                      CAS07360
      I4P1=IOUT2+1                                                      CAS07370
      RETURN                                                            CAS07380
C -------------------- CONSTANTS RELATED TO VARIABLES -----------------CAS07390
      ENTRY CONST3                                                      CAS07400
      JVP1=JV+1                                                         CAS07410
      NEQP1=NEQ+1                                                       CAS07420
      KRHOMU=KSOLVE(JRHO)+KSOLVE(JEMU)                                  CAS07430
C --------------------- IZERO,ILAST AND IEW FOR DIFFERENT VARIABLES     CAS07440
      IZERO(1)=0                                                        CAS07450
      DO 35  J=1,JLAST                                                  CAS07460
      IF(J-JU) 310,301,310                                              CAS07470
310   IF(J-JV) 320,302,320                                              CAS07480
320   IF(J-JP) 330,303,330                                              CAS07490
330   IF(J-JPP) 305,304,305                                             CAS07500
301   IL=NXYU                                                           CAS07510
      ILMAX=(NXMAX-1)*NYMAX                                             CAS07520
      IEW(J)=NY                                                         CAS07530
      GO TO 34                                                          CAS07540
302   IL=NXYV                                                           CAS07550
      ILMAX=NXMAX*(NYMAX-1)                                             CAS07560
      IEW(J)=NYM1                                                       CAS07570
      GO TO 34                                                          CAS07580
303   IL=NXYP                                                           CAS07590
      ILMAX=(NXMAX-2)*(NYMAX-2)                                         CAS07600
      IEW(J)=NYM2                                                       CAS07610
      GO TO 34                                                          CAS07620
304   IL=NY                                                             CAS07630
      ILMAX=NYMAX                                                       CAS07640
      IEW(J)=0                                                          CAS07650
      GO TO 34                                                          CAS07660
305   IL=NXYG                                                           CAS07670
      ILMAX=NXMAX*NYMAX                                                 CAS07680
      IEW(J)=NY                                                         CAS07690
34    ILAST(J)=IZERO(J)+IL                                              CAS07700
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      IF(J.EQ.JLAST) GO TO 35                                           CAS07710
      JP1=J+1                                                           CAS07720
      IZERO(JP1)=IZERO(J)+ILMAX                                         CAS07730
35    CONTINUE                                                          CAS07740
C ---------------------- ASSIGNING VALUES TO JGROUP(JPHI)               CAS07750
      DO 351 J=1,NEQ                                                    CAS07760
      JGROUP(J)=5                                                       CAS07770
      IF(J.EQ.JU) JGROUP(J)=1                                           CAS07780
      IF(J.EQ.JV) JGROUP(J)=2                                           CAS07790
      IF(J.GE.JLIM1.AND.J.LE.JLIM2) JGROUP(J)=3                         CAS07800
      IF(J.GE.JLIM3.AND.J.LE.JLIM4) JGROUP(J)=4                         CAS07810
351   CONTINUE                                                          CAS07820
C ---------------------- ASSIGNING NAMES TO THE TITLE-ARRAY             CAS07830
      ITITLE(JU)=JU                                                     CAS07840
      ITITLE(JV)=JV                                                     CAS07850
      ITITLE(JP)=JP                                                     CAS07860
      ITITLE(JPP)=JPP                                                   CAS07870
      ITITLE(JTKE)=JTKE                                                 CAS07880
      ITITLE(JTED)=JTED                                                 CAS07890
      ITITLE(JRHO)=JRHO                                                 CAS07900
      ITITLE(JEMU)=JEMU                                                 CAS07910
      ITITLE(JH)=JH                                                     CAS07920
      RETURN                                                            CAS07930
C ---------------------- CONSTANTS RELATED TO CHAP. 5 OF MAIN ----------CAS07940
      ENTRY CONST5                                                      CAS07950
      IPREF=IYPREF-1+(IXPREF-2)*NYM2                                    CAS07960
      DO 56 J=1,JLAST                                                   CAS07970
      IF(J.EQ.JPP) GO TO 56                                             CAS07980
      IMON(J)=IYMON+(IXMON-1)*IEW(J)                                    CAS07990
      IF(J.EQ.JP) IMON(J)=IYMON-1+(IXMON-2)*IEW(J)                      CAS08000
56    CONTINUE                                                          CAS08010
      RETURN                                                            CAS08020
      END                                                               CAS08030
      SUBROUTINE ADJUST                                                 CAS08040
      COMMON                                                            CAS08050
     1/CASE1/UINLET,FLOWIN,RPIPE,XPIPE,FXSTEP,HINLET,HWALL              CAS08060
     2/DNY/ DYG(22),DYV(22),FV(22),FVNODE([illegible]22),RDYG(22),RDYV(22)  CAS08070
     2,RSYG(22),RSYV(22),RV(22),RVCB(22),SYG(22),SYV(22),Y(22),YV(22)   CAS08080
     3/DNYDNX/AE(22),AN(22),AP(22),AS(22),AW(22),C(22),D(22),DIFE(22)   CAS08090
     3,DIFN(22),DUW(22), DIFW(22),DU(22),DV(22),EMUE(22),EMUN(22)       CAS08100
     3          ,EMUW(22),HCONE(22),HCONN(22),         HCONW(22)        CAS08110
     3,PHIOLD(22),RHOE(22),RHON(22),        RHOW(22),SP(22),SU(22)      CAS08120
     3,VOLUME(22),CONN(22),CONS(22),CONE(22),CONW(22),ESMPHI(22)        CAS08130
     4/DNX/ DXG(22),DXU(22),FU(22),FUNODE(22),KOUNT(22),RDXG(22)        CAS08140
     4,RDXU(22),RSXG(22),RSXU(22),STORE(22),SXG(22),SXU(22),X(22),XU(22)CAS08150
     5/DJPHI/ IEW(10),ILAST(10),IMON(10),IXNY(10),IZERO(10)             CAS08160
     5,JGROUP(10),KADSOR(10),KSOLVE(10),KRS(10),RELAX(10),RSREF(10)     CAS08170
     5,RSSUM(10),ITITLE(10)                                             CAS08180
      COMMON                                                            CAS08190
     6/DO/CCHECK,DP,FLOWPC,FLOWST,FLOWUP,GREAT,ILINE,IPLRS,IPREF,IPRINT CAS08200
     6,ISTEP ,IX,IX1NY,IX1NY1,IX2NY2,IXMON,IXP1,IXPREF,IYMON,IYPREF      CAS08210
     6,JEMU,JH,JLAST,JLIM1,JLIM2,JLIM3,JLIM4,JP,JPP,JRHO                CAS08220
     6,JU,JV,JVP1,KINPRI,KMPA,KRAD,KRHOMU,KTEST,LABPHI                  CAS08230
     6,LASTEP,LINEF,LINEL,NEQ,NEQP1                                     CAS08240
     6,NODEF,NODEF1,NODEL,NODEL1,NODLP1,NTDMA,NUMCOL                    CAS08250
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     6,NX,NXMAX,NXM1,NXM2,NXYG,NXYP,NXYU,NXYV                           CAS08260
     6,NY,NYMAX,NYM1,NYM2,PI,RSCHEK,RSMAX,TINY                          CAS08270
      COMMON/PROP/EMUREF,PRL(10),PRT(10),RHOREF                         CAS08280
      COMMON/D2D1/ARSL(22,10),RSLINE(22,10)                             CAS08290
      COMMON/D2D2/U(462),V(462),TKE(484),TED(484),H(484),PP(22),P(400)  CAS08300
     7,RHO(484),EMU(484)                                                CAS08310
     7,INLY(10),IOUT(10),KIN,KOUT,RELTKE,RELTED,ISTCH                   CAS08320
      COMMON                                                            CAS08330
     9/TURB/C1,C2,CD,SORTCD,CD25,ECONST,CTAUTW,CYPTW,TAUTW1(22)         CAS08340
     9,TAUTW2(22),YPUST1(22),YPUST2(22)                                 CAS08350
     9,TAULW(22),XPUSLW(22),CTAULW,CXPLW                                CAS08360
     9,GENK(22),FACTKE,FACTED,JTKE,JTED,CAPPA                           CAS08370
     9,INLY1,INLY2,IOUT1,IOUT2,I1M1,I2P1,I3M1,I4P1                      CAS08380
      COMMON/ABC/AREAE                                                  CAS08390
      DIMENSION F(3766)                                                 CAS08400
      DIMENSION DIFS(22),EMUS(22),HCONS(22),RHOS(22)                    CAS08410
      EQUIVALENCE (DIFS(2),DIFN(1)), (EMUS(2),EMUN(1))                  CAS08420
      EQUIVALENCE (RHOS(2),RHON(1)), (AREAE,AREAW)                      CAS08430
      EQUIVALENCE (HCONS(2),HCONN(1))                                   CAS08440
      EQUIVALENCE (F(1),U(1))                                           CAS08450
      DIMENSION A(22),B(22)                                             CAS08460
      EQUIVALENCE(A(1),AN(1)),(B(1),AS(1))                              CAS08470
CHAPTER 1  1  1  1  1   OVERALL-CONTINUITY CORRECTION   1  1  1  1  1 CAS08480
      ENTRY OVACON                                                      CAS08490
      IF(IX.EQ.NXM1) RETURN                                             CAS08500
C---------------------- ADJUST MEAN PRESSURE                            CAS08510
      FLOWST=0.0                                                        CAS08520
      SUMA=0.0                                                          CAS08530
      SUMRA=0.0                                                         CAS08540
      DO 104 IY=NODEF,NODEL                                             CAS08550
      I=IY+IX1NY                                                        CAS08560
      IE=I+NY                                                           CAS08570
      AREA=SYG(IY)*R(IY)                                                CAS08580
      SUMA-SUMA+AREA                                                    CAS08590
      RA=0.5*(RHO(I)+RHO(IE))*AREA                                      CAS08600
      SUMRA=SUMRA+RA                                                    CAS08610
      FLOWST=FLOWST+RA*U(I)                                             CAS08620
104   CONTINUE                                                          CAS08630
      DELU=(FLOWUP-FLOWST)/SUMRA                                        CAS08640
      DP=-DELU*(FLOWUP+FLOWST)/SUMA                                     CAS08650
      FLOWPC=0.0                                                        CAS08660
      DO 105 IY=NODEF,NODEL                                             CAS08670
C---------------------- CORRECT P AT DOWNSTREAM PLANE                   CAS08680
      IP=IY-1+IX2NY2+NYM2                                               CAS08690
      P(IP)=P(IP)+DP                                                    CAS08700
C---------------------- CORRECT U'S                                     CAS08710
      I=IY+IX1NY                                                        CAS08720
      IE=I+NY                                                           CAS08730
      ROE=0.5*(RHO(I)+RHO(IE))                                          CAS08740
      U(I)=U(I)+DELU                                                    CAS08750
      FLOWPC=FLOWPC+U(I)*ROE*SYG(IY)*R(IY)                              CAS08760
105   CONTINUE                                                          CAS08770
      IF(IX.EQ.NXM2) RETURN                                             CAS08780
C---------------------- ADD DP TO ALL OTHER DOWNSTREAM LOCATIONS        CAS08790
      I1=NYM2+NYM2+IX2NY2+1                                             CAS08800
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      DO 1075 IP=I1,NXYP                                                CAS08810
1075  P(IP)=P(IP)+DP                                                    CAS08820
      RETURN                                                            CAS08830
CHAPTER 2  2  2  2  2    CELL-WISE CONTINUITY CORRECTION    2  2  2  2  CAS08840
      ENTRY CELCON                                                      CAS08850
      IF(KSOLVE(JU).EQ.0) GO TO 200                                     CAS08860
      IF(IX.EQ.NXM1) GO TO 200                                          CAS08870
C--------------------- CORRECT U'S ON TDMA LINE                         CAS08880
      DO 21  IY=NODEF,NODEL                                             CAS08890
      I=IY+IX1NY                                                        CAS08900
      U(I)=U(I)+DU(IY)*PP(IY)                                           CAS08910
      IW=I-NY                                                           CAS08920
      U(IW)=U(IW)-DUW(IY)*PP(IY)                                        CAS08930
   21 CONTINUE                                                          CAS08940
C--------------------- CORRECT V'S ON TDMA LINE                         CAS08950
200   IF(KSOLVE(JV).EQ.0) GO TO 210                                     CAS08960
      DO 201  IY=NODEF,NODEL1                                           CAS08970
      IV=IY+IX1NY1                                                      CAS08980
201   V(IV)=V(IV)+DV(IY)*(PP(IY)-PP(IY+1))                              CAS08990
C--------------------- CORRECT P'S ON TDMA LINE                         CAS09000
210   IF(KSOLVE(JPP).EQ.0) RETURN                                       CAS09010
      ICONST=IX2NY2-1                                                   CAS09020
      RF=RELAX(JP)                                                      CAS09030
      DO 211  IY=NODEF,NODEL                                            CAS09040
      IP=IY+ICONST                                                      CAS09050
      P(IP)=P(IP)+PP(IY)*RF                                             CAS09060
211   PP(IY)=0.0                                                        CAS09070
      RETURN                                                            CAS09080
      END                                                               CAS09090
      SUBROUTINE BOUND(LPHI)                                            CAS09100
      COMMON                                                            CAS09110
     1/CASE1/UINLET,FLOWIN,RPIPE,XPIPE,FXSTEP,HINLET,HWALL              CAS09120
     2/DNY/ DYG(22),DYV(22),FV(22),FVNODE(22),R(22),RDYG(22),RDYV(22)   CAS09130
     2,RSYG(22),RSYV(22),RV(22),RVCB(22),SYG(22),SYV(22),Y(22),YV(22)   CAS09140
     3/DNYCNX/AE(22),AN(22),AP(22),AS(22),AW(22),C(22),D(22),DIFE(22)   CAS09150
     3,DIFN(22),DUW(22), DIFW(22),DU(22),DV(22),EMUE(22),EMUN(22)       CAS09160
     3          ,EMUW(22),HCONE(22),HCONN(22),          HCONW(22)       CAS09170
     3,PHIOLD(22),RHOE(22),RHON(22),         RHOW(22),SP(22),SU(22)     CAS09180
     3,VOLUME(22),CONN(22),CONS(22),CONE(22),CONW(22),ESMPHI(22)        CAS09190
     4/DNX/ DXG(22),DXU(22),FU(22),FUNODE(22),KOUNT(22),RDXG(22)        CAS09200
     4,RDXU(22),RSXG(22),RSXU(22),STORE(22),SXG(22),SXU(22),X(22),XU(22)CAS09210
     5/DJPHI/ IEW(10),ILAST(10),IMON(10),IXNY(10),IZERO(10)             CAS09220
     5,JGROUP(10),KADSOR(10),KSOLVE(10),KRS(10),RELAX(10),RSREF(10)     CAS09230
     5,RSSUM(10),ITITLE(10)                                             CAS09240
      COMMON                                                            CAS09250
     6/DO/CCHECK,DP,FLOWPC,FLOWST,FLOWUP,GREAT,ILINE,IPLRS,IPREF,IPRINT CAS09260
     6,ISTEP  ,IX,IX1NY,IX1NY1,IX2NY2,IXMON,IXP1,IXPREF,IYMON,IYPREF    CAS09270
     6,JEMU,JH,JLAST,JLIM1,JLIM2,JLIM3,JLIM4,JP,JPP,JRHO                CAS09280
     6,JU,JV,JVP1,KINPRI,KMPA,KRAD,KRHOMU,XTEST,LABPHI                  CAS09290
     6,LASTEP,LINEF,LINEL,NEQ,NEQP1                                     CAS09300
     6,NODEF,NODEF1,NODEL,NODEL1,NODLP1,NTDMA,NUMCOL                    CAS09310
     6,NX,NXMAX,NXM1,NXM2,NXYG,NXYP,NXYU,NXYV                           CAS09320
     6,NY,NYMAX,NYM1,NYM2,PI,RSCHEK,RSMAX,TINY                          CAS09330
      COMMON/PRCP/EMUREF,PRL(10),PRT(10),RHOREF                         CAS09340
      COMMON/D2D1/ARSL(22,10),RSLINE(22,10)                             CAS09350
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      COMMON/D2D2/U(462),V(462),TKE(484),TED(484),H(484),PP(22),P(400)  CAS09360
     7,RHO(484),EMU(484)                                                CAS09370
     7,INLY(10),IOUT(10),KIN,KOUT,RELTKE,RELTED,ISTCH                   CAS09380
      COMMON                                                            CAS09390
     9/TURB/C1,C2,CD,SQRTCD,CD25,ECONST,CTAUTW,CYPTW,TAUTW1(22)         CAS09400
     9,TAUTW2(22),YPUST1(22),YPUST2(22)                                 CAS09410
     9,TAULW(22),XPUSLW(22),CTAULW,CXPLW                                CAS09420
     9,GENK(22),FACTKE,FACTED,JTKE,JTED,CAPPA                           CAS09430
     9,INLY1,INLY2,IOUT1,IOUT2,I1M1,I2P1,I3M1,I4P1                      CAS09440
      COMMON/ABC/AREAE                                                  CAS09450
      DIMENSION F(3766)                                                 CAS09460
      DIMENSION DIFS(22),EMUS(22),HCONS(22),RHOS(22)                    CAS09470
      EQUIVALENCE (DIFS(2),DIFN(1)), (EMUS(2),EMUN(1))                  CAS09480
      EQUIVALENCE (RHOS(2),RHON(1)), (AREAE,AREAW)                      CAS09490
      EQUIVALENCE (HCONS(2),HCONN(1))                                   CAS09500
      EQUIVALENCE (F(1),U(1))                                           CAS09510
      DIMENSION A(22),B(22)                                             CAS09520
      EQUIVALENCE(A(1),AN(1)),(B(1),AS(1))                              CAS09530
CHAPTER 1  1  1  1  1     PRELIMINARIES    1  1  1  1  1  1  1  1  1  1 CAS09540
      JPHI=LPHI                                                         CAS09550
      IF(JPHI.EQ.JU) GO TO 20                                           CAS09560
      IF(JPHI.EQ.JH) GO TO 30                                           CAS09570
      IF(JPHI.EQ.JEMU) GO TO 40                                         CAS09580
      IF(JPHI.EQ.JTKE) GO TO 50                                         CAS09590
      IF(JPHI.EQ.JTED) GO TO 60                                         CAS09600
      IF(JPHI.EQ.JV) GO TO 70                                           CAS09610
      IF(JPHI.EQ.JRHO) GO TO 80                                         CAS09620
      RETURN                                                            CAS09630
CHAPTER 2  2  2  2  2     UPDATING OF U ON BOUNDARIES     2  2  2  2  2 CAS09640
   20 CONTINUE                                                          CAS09650
      RETURN                                                            CAS09660
30    CONTINUE                                                          CAS09670
CHAPTER 3  3  3  3  3     UPDATING OF H ON BOUNDARIES     3  3  3  3  3 CAS09680
      RETURN                                                            CAS09690
   40 CONTINUE                                                          CAS09700
CHAPTER 4 4 4 4 4                                                       CAS09710
C--------------LADLE FREE SURFACE                                       CAS09720
      IF(IX.NE.2) RETURN                                                CAS09730
      DO 41 IY=2,NYM1                                                   CAS09740
      I=IY+IX1NY                                                        CAS09750
      IW=I-NY                                                           CAS09760
      IF(IY.GE.INLY1.AND.IY.LE.INLY2) GO TO 41                          CAS09770
      IF(IY.GE.IOUT1.AND.IY.LE.IOUT2) GO TO 41                          CAS09780
      EMU(IW)=EMU(I)                                                    CAS09790
   41 CONTINUE                                                          CAS09800
      RETURN                                                            CAS09810
CHAPTER 5 5 5 5   UPDATING OF TKE                                       CAS09820
   50 CONTINUE                                                          CAS09830
C-------FREE SURFACE                                                    CAS09840
      IF(IX.NE.2) GO TO 5001                                            CAS09850
      DO 501 IY=2,I1M1                                                  CAS09860
      I=IY+IX1NY                                                        CAS09870
      IW=I-NY                                                           CAS09880
  501 TKE(IW)=TKE(I)                                                    CAS09890
      DO 502 IY=I2P1,I3M1                                               CAS09900
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      I=IY+IX1NY                                                        CAS09910
      IW=I-NY                                                           CAS09920
  502 TKE(IW)=TKE(I)                                                    CAS09930
      DO 503 IY=I4P1,NYM1                                               CAS09940
      I=IY+IX1NY                                                        CAS09950
      IW=I-NY                                                           CAS09960
  503 TKE(IW)=TKE(I)                                                    CAS09970
 5001 CONTINUE                                                          CAS09980
C---------LADLE WALL                                                    CAS09990
      IL=1+IX1NY                                                        CAS10000
      IR=NY+IX1NY                                                       CAS10010
      TKE(IL)=0.0                                                       CAS10020
      TKE(IR)=0.0                                                       CAS10030
      RETURN                                                            CAS10040
   60 CONTINUE                                                          CAS10050
CHAPTER 6 6 6 6 6  UPDATING OF TED                                      CAS10060
C-------FREE SURFACE                                                    CAS10070
      IF(IX.NE.2) GO TO 6001                                            CAS10080
      DO 601 IY=2,I1M1                                                  CAS10090
      I=IY+IX1NY                                                        CAS10100
      IW=I-NY                                                           CAS10110
  601 TED(IW)=TED(I)                                                    CAS10120
      DO 602 IY=I2P1,I3M1                                               CAS10130
      I=IY+IX1NY                                                        CAS10140
      IW=I-NY                                                           CAS10150
  602 TED(IW)=TED(I)                                                    CAS10160
      DO 603 IY=I4P1,NYM1                                               CAS10170
      I=IY+IX1NY                                                        CAS10180
      IW=I-NY                                                           CAS10190
  603 TED(IW)=TED(I)                                                    CAS10200
 6001 CONTINUE                                                          CAS10210
C----------LADLE WALL                                                   CAS10220
      IL=1+IX1NY                                                        CAS10230
      IR=NY+IX1NY                                                       CAS10240
      TED(IL)=0.0                                                       CAS10250
      TED(IR)=0.0                                                       CAS10260
      RETURN                                                            CAS10270
CHAPTER 7 7 7 7    UPDATING OF V                                        CAS10280
   70 CONTINUE                                                          CAS10290
C---------FREE SURFACE                                                  CAS10300
      IF(IX.NE.2) RETURN                                                CAS10310
      III=I1M1-1                                                        CAS10320
      DO 701 IY=2,III                                                   CAS10330
      I=IY+IX1NY1                                                       CAS10340
      IW=I-NYM1                                                         CAS10350
  701 V(IW)=V(I)                                                        CAS10360
      III2=I3M1-1                                                       CAS10370
      DO 702 IY=I2P1,III2                                               CAS10380
      I=IY+IX1NY1                                                       CAS10390
      IW=I-NYM1                                                         CAS10400
  702 V(IW)=V(I)                                                        CAS10410
      DO 703 IY=I4P1,NYM2                                               CAS10420
      I=IY+IX1NY1                                                       CAS10430
      IW=I-NYM1                                                         CAS10440
  703 V(IW)=V(I)                                                        CAS10450
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      RETURN                                                            CAS10460
CHPTER 8 8 8 8  UPDATING OF RHO                                         CAS10470
   80 CONTINUE                                                          CAS10480
      RETURN                                                            CAS10490
      END                                                               CAS10500
      SUBROUTINE SOURCE(LPHI)                                           CAS10510
      COMMON                                                            CAS10520
     1/CASE1/UINLET,FLOWIN,RPIPE,XPIPE,FXSTEP,HINLET,HWALL              CAS10530
     2/DNY/ DYG(22),DYV(22),FV(22),FVNODE(22),R(22),RDYG(22),RDYV(22)   CAS10540
     2,RSYG(22),RSYV(22),RV(22),RVCB(22),SYG(22),SYV(22),Y(22),YV(22)   CAS10550
     3/DNYONX/AE(22),AN(22),AP(22),AS(22),AW(22),C(22),D(22),DIFE(22)   CAS10560
     3,DIFN(22),DUW(22), DIFW(22),DU(22),DV(22),EMUE(22),EMUN(22)       CAS10570
     3         ,EMUW(22),HCONE(22),HCONN(22),            HCONW(22)       CAS10580
     3,PHIOLD(22),RHOE(22),RHON(22),         RHOW(22),SP(22),SU(22)     CAS10590
     3,VOLUME(22),CONN(22),CONS(22),CONE(22),CONW(22),ESMPHI(22)        CAS10600
     4/DNX/ DXG(22),DXU(22),FU(22),FUNODE(22),KOUNT(22),RDXG(22)        CAS10610
     4,RDXU(22),RSXG(22),RSXU(22),STORE(22),SXG(22),SXU(22),X(22),XU(22)CAS10620
     5/DIPHI/ IEW(10),ILAST(10),IMON(10),IXNY(10),IZERO(10)             CAS10630
     5,JGROUP(10),KADSOR(10),KSOLVE(10),KRS(10),RELAX(10),RSREF(10)     CAS10640
     5,RSSUM(10),ITITLE(10)                                             CAS10650
      COMMON                                                            CAS10660
     6/DD/CCHECK,DP,FLOWPC,FLOWST,FLOWUP,GREAT,ILINE,IPLRS,IPREF,IPRINT CAS10670
     6,ISTEP ,IX,IX1NY,IX1NY1,IX2NY2,IXMON,IXP1,IXPREF,IYMON,IYPREF     CAS10680
     6,JEMU,JH,JLAST,JLIM1,JLIM2,JLIM3,JLIM4,JP,JPP,JRHO                CAS10690
     6,JU,JV,JVP1,KINPRI,KMPA,KRAD,KRHOMU,KTEST,LABPHI                  CAS10700
     6,LASTEP,LINEF,LINEL,NEQ,NEQP1                                     CAS10710
     6,NODEF,NODEF1,NODEL,NODEL1,NODLP1,NTDMA,NUMCOL                    CAS10720
     6,NX,NXMAX,NXM1,NXM2,NXYG,NXYP,NXYU,NXYV                           CAS10730
     6,NY,NYMAX,NYM1,NYM2,PI,RSCHEK,RSMAX,TINY                          CAS10740
      COMMON/PROP/EMUREF,PRL(10),PRT(10),RHOREF                         CAS10750
      COMMON/D2D1/ARSL(22,10),RSLINE(22,10)                             CAS10760
      COMMON/D2D2/U(462),V(462),TKE(484),TED(484),H(484),PP(22),P(400)  CAS10770
     7,RHO(484),EMU(484)                                                CAS10780
     7,INLY(10),IOUT(10),KIN,KOUT,RELTKE,RELTED,ISTCH                   CAS10790
      COMMON                                                            CAS10800
     9/TURB/C1,C2,CD,SORTCD,CD25,ECONST,CTAUTW,CYPTW,TAUTW1(22)         CAS10810
     9,TAUTW2(22),YPUST1(22),YPUST2(22)                                 CAS10820
     9,TAULW(22),XPUSLW(22),CTAULW,CXPLW                                CAS10830
     9,GENK(22),FACTKE,FACTED,JTKE,JTED,CAPPA                           CAS10840
     9,INLY1,INLY2,IOUT1,IOUT2,I1M1,I2P1,I3M1,I4P1                      CAS10850
      COMMON/ABC/AREAE                                                  CAS10860
      DIMENSION F(3766)                                                 CAS10870
      DIMENSION DIFS(22),EMUS(22),HCONS(22),RHOS(22)                    CAS10880
      EQUIVALENCE (DIFS(2),DIFN(1)), (EMUS(2),EMUN(1))                  CAS10890
      EQUIVALENCE (RHOS(2),RHON(1)), (AREAE,AREAW)                      CAS10900
      EQUIVALENCE (HCONS(2),HCONN(1))                                   CAS10910
      EQUIVALENCE (F(1),U(1))                                           CAS10920
      DIMENSION A(22),B(22)                                             CAS10930
      EQUIVALENCE(A(1),AN(1)),(B(1),AS(1))                              CAS10940
CHAPTER 1  1  1  1  1    PRELIMINARIES    1  1  1  1  1  1  1  1  1  1  CAS10950
      JPHI=LPHI                                                         CAS10960
      IF(JPHI.EQ.JU) GO TO 20                                           CAS10970
      IF(JPHI.EQ.JV) GO TO 30                                           CAS10980
      IF(JPHI.EQ.JPP) GO TO 40                                          CAS10990
      IF(JPHI.EQ.JH) GO TO 50                                           CAS11000
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      IF(JPHI.EQ.JTKE) GO TO 60                                         CAS11010
      IF(JPHI.EQ.JTED) GO TO 70                                         CAS11020
      RETURN                                                            CAS11030
CHAPTER 2  2  2  2  2    ADDITIONAL SOURCE TERMS FOR U    2  2  2  2    CAS11040
20    CONTINUE                                                          CAS11050
      RETURN                                                            CAS11060
CHAPTER 3  3  3  3  3    ADDITIONAL SOURCE TERMS FOR V    3  3  3  3    CAS11070
30    CONTINUE                                                          CAS11080
      RETURN                                                            CAS11090
CHAPTER 4  4  4  4  4    ADDITIONAL SOURCE TERMS FOR P'   4  4  4  4    CAS11100
40    CONTINUE                                                          CAS11110
      RETURN                                                            CAS11120
CHAPTER 5  5  5  5  5    ADDITIONAL SOURCE TERMS FOR H    5  5  5  5    CAS11130
50    CONTINUE                                                          CAS11140
      RETURN                                                            CAS11150
CHAPTER 6 6 6 6 6 6 6     ADDITIONAL SOURCE TERM FOR K                  CAS11160
   60 CONTINUE                                                          CAS11170
      C2M1=C2-1.0                                                       CAS11180
      DO 61  IY=NODEF,NODEL                                             CAS11190
      I=IY+IX1NY                                                        CAS11200
      IW=I-NY                                                           CAS11210
      IN=I+1                                                            CAS11220
      INW=IW+1                                                          CAS11230
      IS=I-1                                                            CAS11240
      ISW=IW-1                                                          CAS11250
      IV=IY+IX1NY1                                                      CAS11260
      ISV=IV-1                                                          CAS11270
      IEV=IV+NYM1                                                       CAS11280
      ISEV=IEV-1                                                        CAS11290
      IWV=IV-NYM1                                                       CAS11300
      ISWV=IWV-1                                                        CAS11310
      DUDX=(U(I)-U(IW))*RSXG(IX)                                        CAS11320
      DVDY=(V(IV)-V(ISV))*RSYG(IY)                                      CAS11330
      DUDY=0.5*(U(IN)+U(INW)-U(IS)-U(ISW))/(Y(IY+1)-Y(IY-1))            CAS11340
      DVDX=0.5*(V(IEV)+V(ISEV)-V(IWV)-V(ISWV))/(X(IX+1)-X(IX-           CAS11350
     1   1))                                                            CAS11360
      IF(KRAD.EQ.2) GO TO 63                                            CAS11370
   62 GENK(IY)=(EMU(I)-EMUREF)*(2.0*(DUDX**2+DVDY**2)+(DUDY+            CAS11380
     1   DVDX)**2)                                                      CAS11390
      GO TO 64                                                          CAS11400
   63 VP=V(ISV)+(V(IV)-V(ISV))*FVNODE(IY)                               CAS11410
      VPDR=VP/R(IY)                                                     CAS11420
      GENK(IY)=(2.*(DUDX**2+DVDY**2+VPDR**2)+(DUDY+DVDX)**2)*           CAS11430
     1   (EMU(I)-EMUREF)                                                CAS11440
   64 CONTINUE                                                          CAS11450
      SU(IY)=(1.5*GENK(IY)+C2M1*RHO(I)*TED(I))*VOLUME(IY)               CAS11460
   61 SP(IY)=-(C2*RHO(I)*TED(I)+0.5*GENK(IY))*VOLUME(IY)/               CAS11470
     1  (TKE(I)+TINY)                                                   CAS11480
      RETURN                                                            CAS11490
CHAPTER 7 76 7 7 7 TURBULENT ENERGY DISSIPATION 7 7 7 7                 CAS11500
   70  CONTINUE                                                         CAS11510
      C2M1=C2-1.0                                                       CAS11520
      TC2M1=2.0*C2-1.0                                                  CAS11530
      DO 71  IY=NODEF,NODEL                                             CAS11540
      I=IY+IX1NY                                                        CAS11550
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      ETVDK=TED(I)*VOLUME(IY)/(TKE(I)+TINY)                             CAS11560
      SU(IY)=(C1*GENK(IY)+C2M1*RHO(I)*TED(I))*ETVDK                     CAS11570
   71 SP(IY)=-RHO(IY)*TC2M1*ETVDK                                       CAS11580
      RETURN                                                            CAS11590
      END                                                               CAS11600
      SUBROUTINE MODIFY(LPHI)                                           CAS11610
      COMMON                                                            CAS11620
     1/CASE1/UINLET,FLOWIN,RPIPE,XPIPE,FXSTEP,HINLET,HWALL              CAS11630
     2/DNY/ DYG(22),DYV(22),FV(22),FVNODE(22),R(22),RDYG(22),RDYV(22)   CAS11640
     2,RSYG(22),RSYV(22),RV(22),RVCB(22),SYG(22),SYV(22),Y(22),YV(22)   CAS11650
     3/DNYONX/AE(22),AN(22),AP(22),AS(22),AW(22),C(22),D(22),DIFE(22)   CAS11660
     3,DIFN(22),DUW(22), DIFW(22),DU(22),DV(22),EMUE(22),EMUN(22)       CAS11670
     3         ,EMUW(22),HCONE(22),HCONN(22),           HCONW(22)       CAS11680
     3,PHIOLD(22),RHOE(22),RHON(22),          RHOW(22),SP(22),SU(22)    CAS11690
     3,VOLUME(22),CONN(22),CONS(22),CONE(22),CONW(22),ESMPHI(22)        CAS11700
     4/DNX/ DXG(22),DXU(22),FU(22),FUNODE(22),KOUNT(22),RDXG(22)        CAS11710
     4,RDXU(22),RSXG(22),RSXU(22),STORE(22),SXG(22),SXU(22),X(22),XU(22)CAS11720
     5/DJPHI/ IEW(10),ILAST(10),IMON(10),IXNY(10),IZERO(10)             CAS11730
     5,JGROUP(10),KADSOR(10),KSOLVE(10),KRS(10),RELAX(10),RSREF(10)     CAS11740
     5,RSSUM(10),ITITLE(10)                                             CAS11750
      COMMON                                                            CAS11760
     6/DO/CCHECK,DP,FLOWPC,FLOWST,FLOWUP,GREAT,ILINE,IPLRS,IPREF,IPRINT CAS11770
     6,ISTEP ,IX,IX1NY,IX1NY1,IX2NY2,IXMON,IXP1,IXPREF,IYMON,IYPREF     CAS11780
     6,JEMU,JH,JLAST,JLIM1,JLIM2,JLIM3,JLIM4,JP,JPP,JRHO                CAS11790
     6,JU,JV,JVP1,KINPRI,KMPA,KRAD,KRHOMU,KTEST,LABPHI                  CAS11800
     6,LASTEP,LINEF,LINEL,NEQ,NEQP1                                     CAS11810
     6,NODEF,NODEF1,NODEL,NODEL1,NODLP1,NTDMA,NUMCOL                    CAS11820
     6,NX,NXMAX,NXM1,NXM2,NXYG,NXYP,NXYU,NXYV                           CAS11830
     6,NY,NYMAX,NYM1,NYM2,PI,RSCHEK,RSMAX,TINY                          CAS11840
      COMMON/PROP/EMUREF,PRL(10),PRT(10),RHOREF                         CAS11850
      COMMON/D2D1/APSL(22,10),RSLINE(22,10)                             CAS11860
      COMMON/D2D2/U(462),V(462),TKE(484),TED(484),H(484),PP(22),P(400)  CAS11870
     7,RHO(484),EMU(484)                                                CAS11880
     7,INLY(10),IOUT(10),KIN,KOUT,RELTKE,RELTED,ISTCH                   CAS11890
      COMMON                                                            CAS11900
     9/TURB/C1,C2,CD,SQRTCD,CD25,ECONST,CTAUTW,CYPTW,TAUTW1(22)         CAS11910
     9,TAUTW2(22),YPUST1(22),YPUST2(22)                                 CAS11920
     9,TAULW(22),XPUSLW(22),CTAULW,CXPLW                                CAS11930
     9,GENK(22),FACTKE,FACTED,JTKE,JTED,CAPPA                           CAS11940
     9,INLY1,INLY2,IOUT1,IOUT2,I1M1,I2P1,I3M1,I4P1                      CAS11950
      COMMON/ABC/AREAE                                                  CAS11960
      DIMENSION F(3766)                                                 CAS11970
      DIMENSION DIFS(22),EMUS(22),HCONS(22),RHOS(22)                    CAS11980
      EQUIVALENCE (DIFS(2),DIFN(1)), (EMUS(2),EMUN(1))                  CAS11990
      EQUIVALENCE (RHOS(2),RHON(1)), (AREAE,AREAW)                      CAS12000
      EQUIVALENCE (HCONS(2),HCONN(1))                                   CAS12010
      EQUIVALENCE (F(1),U(1))                                           CAS12020
      DIMENSION A(22),B(22)                                             CAS12030
      EQUIVALENCE(A(1),AN(1)),(B(1),AS(1))                              CAS12040
CHAPTER 1  1  1  1  1    PRELIMINARIES    1  1  1  1  1  1  1  1  1  1  CAS12050
      JPHI=LPHI                                                         CAS12060
      IF(JPHI.EQ.JU) GO TO 20                                           CAS12070
      IF(JPHI.EQ.JV) GO TO 30                                           CAS12080
      IF(JPHI.EQ.JPP) GO TO 40                                          CAS12090
      IF(JPHI.EQ.JH) GO TO 50                                           CAS12100
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      IF(JPHI.EQ.JTKE) GO TO 60                                         CAS12110
      IF(JPHI.EQ.JTED) GO TO 70                                         CAS12120
      RETURN                                                            CAS12130
CHAPTER 2  2  2  2  2  . MODIFICATIONS TO THE U-EQUATION COEFFICIENTS   CAS12140
20    CONTINUE                                                          CAS12150
COMMENT -------AT LET-SIDE WALL                                         CAS12160
      AS(2)=0.0                                                         CAS12170
      I=2+IX1NY                                                         CAS12180
      TAUA1=0.5*(TAUTW1(IX)+TAUTW1(IXP1))                               CAS12190
      TAUA1=ABS(TAUA1)                                                  CAS12200
      UI=U(I)                                                           CAS12210
      ABSUI=ABS(UI)                                                     CAS12220
      SP(2)=SP(2)-TAUA1*SXU(IX)/ABSUI                                   CAS12230
C   ---------AT RIGHT SIDE WALL                                         CAS12240
      I=NYM1+IX1NY                                                      CAS12250
      AN(NYM1)=0.0                                                      CAS12260
      TAUA2=0.5*(TAUTW2(IX)+TAUTW2(IXP1))                               CAS12270
      TAUA2=ABS(TAUA2)                                                  CAS12280
      UI=U(I)                                                           CAS12290
      ABSUI=ABS(UI)                                                     CAS12300
      SP(NYM1)=SP(NYM1)-TAUA2*SXU(IX)/ABSUI                             CAS12310
C----------NEAR FREE SURFACE                                            CAS12320
      IF(IX.NE.2)  GO TO 250                                            CAS12330
      DO 210 IY=2,I1M1                                                  CAS12340
  210 AW(IY)=0.0                                                        CAS12350
      DO 211 IY=I2P1,I3M1                                               CAS12360
  211 AW(IY)=0.0                                                        CAS12370
      DO 212 IY=I4P1,NYM1                                               CAS12380
  212 AW(IY)=0.0                                                        CAS12390
  250 CONTINUE                                                          CAS12400
      IF(IX.NE.NXM2) RETURN                                             CAS12410
      DO 251 I=2,NYM1                                                   CAS12420
  251 AE(IY)=0.0                                                        CAS12430
      RETURN                                                            CAS12440
30    CONTINUE                                                          CAS12450
CHAPTER 3  3  3  3  3   MODIFICATIONS TO THE V-EQUATION COEFFICIENTS    CAS12460
C -------AT FREE SURFACE                                                CAS12470
      IF(IX.NE.2) GO TO 310                                             CAS12480
      III=I1M1-1                                                        CAS12490
      DO 311 IY=2,III                                                   CAS12500
  311 AW(IY)=0.0                                                        CAS12510
      III2=I3M1-1                                                       CAS12520
      DO 312 IY=I2P1,III2                                               CAS12530
  312 AW(IY)=0.0                                                        CAS12540
      DO 313 IY=I4P1,NYM2                                               CAS12550
  313 AW(IY)=0.0                                                        CAS12560
  310 IF(IX.NE.NXM1) RETURN                                             CAS12570
      DO 340 IY=2,NYM2                                                  CAS12580
      I=IY+IX1NY1                                                       CAS12590
      AE(IY)=0.0                                                        CAS12600
      TAUA=0.5*(TAULW(IY)+TAULW(IY+1))                                  CAS12610
      TAUA=ABS(TAUA)                                                    CAS12620
      VI=V(I)                                                           CAS12630
      ABSVI=ABS(VI)                                                     CAS12640
  340 SP(IY)=SP(IY)-TAUA*SYV(IY)/ABSVI                                  CAS12650
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      RETURN                                                            CAS12660
CHAPTER 4  4  4  4  4    MODIFICATIONS TO THE P'-EQUATION COEFFICIENTS  CAS12670
40    CONTINUE                                                          CAS12680
C---------------------- PUT P'=0 NEAR EXIT                              CAS12690
      AS(2)=0.0                                                         CAS12700
      AN(NYM1)=0.0                                                      CAS12710
      IF(IX.NE.NXM1) RETURN                                             CAS12720
      DO 47 IY=2,NYM1                                                   CAS12730
   47 AE(IY)=0.0                                                        CAS12740
      RETURN                                                            CAS12750
CHAPTER 5  5  5  5  5    MODIFICATIONS TO THE H-EQUATION COEFFICIENTS   CAS12760
50    CONTINUE                                                          CAS12770
      RETURN                                                            CAS12780
CHAPTER 6 6 6 6 6  ----MODIFY OF K-EQUATION                             CAS12790
   60 CONTINUE                                                          CAS12800
      SP1=0.0                                                           CAS12810
      SU1=0.0                                                           CAS12820
      SP2=0.0                                                           CAS12830
      SU2=0.0                                                           CAS12840
C-------------FREE SURFACE                                              CAS12850
      IF(IX.NE.2) GO TO 610                                             CAS12860
      DO 61 IY=2,I1M1                                                   CAS12870
   61 AW(IY)=0.0                                                        CAS12880
      DO 62 IY=I2P1,I3M1                                                CAS12890
   62 AW(IY)=0.0                                                        CAS12900
      DO 63 IY=I4P1,NYM1                                                CAS12910
   63 AW(IY)=0.0                                                        CAS12920
      AN(NYM1)=0.0                                                      CAS12930
      AS(2)=0.0                                                         CAS12940
  610 CONTINUE                                                          CAS12950
C---------LEFT SIDE WALL                                                CAS12960
      IY1=2                                                             CAS12970
      AS(IY1)=0.0                                                       CAS12980
      I=IY1+IX1NY                                                       CAS12990
      IW1=I-NY                                                          CAS13000
      INW=IW1+1                                                         CAS13010
      IN=I+1                                                            CAS13020
      UP=U(IW1)+(U(I)-U(IW1))*FUNODE(IX)                                CAS13030
      UN=U(INW)+(U(IN)-U(INW))*FUNODE(IX)                               CAS13040
      UN=ABS(0.5*(UP+UN))                                               CAS13050
      IF(IX.EQ.2.AND.UN.LE.TINY) UN=TINY                                CAS13060
      ABSTAU=ABS(TAUTW1(IX))                                            CAS13070
      SU(IY1)=ABSTAU*UN*SXG(IX)*R(IY)                                   CAS13080
      SP(IY1)=-CD*RHO(I)**2*TKE(I)*UN*SXG(IX)*R(IY1)/(ABSTAU+TINY)      CAS13090
      SU1=SU(2)                                                         CAS13100
      SP1=SP(2)                                                         CAS13110
C----------RIGHT SIDE WALL                                              CAS13120
      IY2=NYM1                                                          CAS13130
      AN(IY2)=0.0                                                       CAS13140
      I=IY2+IX1NY                                                       CAS13150
      IW=I-NY                                                           CAS13160
      ISW=IW-1                                                          CAS13170
      IS=I-1                                                            CAS13180
      UP=U(IW)+(U(I)-U(IW))*FUNODE(IX)                                  CAS13190
      US=U(ISW)+(U(IS)-U(ISW))*FUNODE(IX)                               CAS13200
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      US=ABS(0.5*(UP+US))                                               CAS13210
      IF(IX.EQ.2.AND.US.LE.TINY) US=TINY                                CAS13220
      ABSTAU=ABS(TAUTW2(IX))                                            CAS13230
      SU(IY2)=ABSTAU*US*SXG(IX)*R(IY2)                                  CAS13240
      SP(IY2)=-CD*RHO(I)**2*TKE(I)*US*SXG(IX)*R(IY2)/(ABSTAU+TINY)      CAS13250
      SU2=SU(IY2)                                                       CAS13260
      SP2=SP(IY2)                                                       CAS13270
C-----------LADLE BOTTOM                                                CAS13280
      IF(IX.NE.NXM1) RETURN                                             CAS13290
      DO 650 IY=2,NYM2                                                  CAS13300
      AE(IY)=0.0                                                        CAS13310
      I=IY+IX1NY                                                        CAS13320
      IV=IY+IX1NY1                                                      CAS13330
      ISV=IV-1                                                          CAS13340
      ISWV=ISV-NYM1                                                     CAS13350
      IWV=IV-NYM1                                                       CAS13360
      VP=V(ISV)+(V(IV)-V(ISV))*FVNODE(IY)                               CAS13370
       VW=V(ISWV)+(V(IWV)-V(ISWV))*FVNODE(IY)                           CAS13380
      VW=ABS(0.5*(VP+VW))                                               CAS13390
      ABSTAU=ABS(TAULW(IY))                                             CAS13400
      SU(IY)=ABSTAU*VW*SYG(IY)*R(IY)                                    CAS13410
      SP(IY)=-CD*RHO(I)**2*TKE(I)*VW*SYG(IY)*R(IY)/(ABSTAU+TINY)        CAS13420
  650 CONTINUE                                                          CAS13430
      SU(2)=SU(2)+SU1                                                   CAS13440
      SU(NYM1)=SU(NYM1)+SU2                                             CAS13450
      SP(2)=SP(2)+SP1                                                   CAS13460
      SP(NYM1)=SP(NYM1)+SP2                                             CAS13470
  660 CONTINUE                                                          CAS13480
      RETURN                                                            CAS13490
CHAPTER 7 7 7 7 7 7 MODIFY TO THE E-EQUATION COEFF.                     CAS13500
   70 CONTINUE                                                          CAS13510
      SP1=0.0                                                           CAS13520
      SU1=0.0                                                           CAS13530
C                                                                       CAS13540
C                                                                       CAS13550
      IF(IX.NE.2) GO TO 750                                             CAS13560
      DO 71 IY=2,I1M1                                                   CAS13570
   71 AW(IY)=0.0                                                        CAS13580
      DO 72 IY=I2P1,I3M1                                                CAS13590
   72 AW(IY)=0.0                                                        CAS13600
      DO 73 IY=I4P1,NYM1                                                CAS13610
   73 AW(IY)=0.0                                                        CAS13620
  750 CONTINUE                                                          CAS13630
C-----------LADLE WALL LEFT                                             CAS13640
      IY1=2                                                             CAS13650
      I=IY1+IX1NY                                                       CAS13660
      CDK=SQRTCD*TKE(I)                                                 CAS13670
      TEDI=CDK*SQRT(CDK)/(CAPPA*DYG(NY))                                CAS13680
      PHIOLD(IY)=TEDI                                                   CAS13690
      SU(IY1)=GREAT*TEDI                                                CAS13700
      SP(IY1)=-GREAT                                                    CAS13710
      SU1=SU(2)                                                         CAS13720
      SP1=SP(2)                                                         CAS13730
C-----------LADLE WALL RIGHT                                            CAS13740
      IY2=NYM1                                                          CAS13750
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      I=IY2+IX1NY                                                       CAS13760
      CDK=SQRTCD*TKE(I)                                                 CAS13770
      TEDI=CDK*SQRT(CDK)/(CAPPA*DYG(NY))                                CAS13780
      PHIOLD(IY2)=TEDI                                                  CAS13790
      SU(IY2)=GREAT*TEDI                                                CAS13800
      SP(IY2)=-GREAT                                                    CAS13810
      SU2=SU(NYM1)                                                      CAS13820
      SP2=SP(NYM1)                                                      CAS13830
  760 CONTINUE                                                          CAS13840
C------------LADLE BOTTOM                                               CAS13850
      IF(IX.NE.NXM1) RETURN                                             CAS13860
      TERM=1./(CAPPA*DXG(NX))                                           CAS13870
      DO 700 IY=2,NYM1                                                  CAS13880
      I=IY+IX1NY                                                        CAS13890
      CDK=SQRTCD*TKE(I)                                                 CAS13900
      TEDI=CDK*SQRT(CDK)*TERM                                           CAS13910
      PHIOLD(IY)=TEDI                                                   CAS13920
      SU(IY)=GREAT*TEDI                                                 CAS13930
      SP(IY)=-GREAT                                                     CAS13940
  700 CONTINUE                                                          CAS13950
      SU(2)=SU(2)+SU1                                                   CAS13960
      SP(2)=SP(2)+SP1                                                   CAS13970
      SU(NYM1)=SU(NYM1)+SU2                                             CAS13980
      SP(NYM1)=SP(NYM1)+SP2                                             CAS13990
  701 CONTINUE                                                          CAS14000
      RETURN                                                            CAS14010
      END                                                               CAS14020
      SUBROUTINE GEOM                                                   CAS14030
      COMMON                                                            CAS14040
     1/CASE1/UINLET,FLOWIN,RPIPE,XPIPE,FXSTEP,HINLET,HWALL              CAS14050
     2/DNY/ DYG(22),DYV(22),FV(22),FVNODE(22),R(22),RDYG(22),RDYV(22)   CAS14060
     2,RSYG(22),RSYV(22),RV(22),RVCB(22),SYG(22),SYV(22),Y(22),YV(22)   CAS14070
     3/DNYONX/AE(22),AN(22),AP(22),AS(22),AW(22),C(22),D(22),DIFE(22)   CAS14080
     3,DIFN(22),DUW(22), DIFW(22),DU(22),DV(22),EMUE(22),EMUN(22)       CAS14090
     3         ,EMUW(22),HCONE(22),HCONN(22),          HCONW(22)        CAS14100
     3,PHIOLD(22),RHOE(22),RHON(22),        RHOW(22),SP(22),SU(22)      CAS14110
     3,VOLUME(22),CONN(22),CONS(22),CONE(22),CONW(22),ESMPHI(22)        CAS14120
     4/DNX/ DXG(22),DXU(22),FU(22),FUNODE(22),KOUNT(22),RDXG(22)        CAS14130
     4,RDXU(22),RSXG(22),RSXU(22),STORE(22),SXG(22),SXU(22),X(22),XU(22)CAS14140
     5/DUPHI/ IEW(10),ILAST(10),IMON(10),IXNY(10),IZERO(10)             CAS14150
     5,JGROUP(10),KADSOR(10),KSOLVE(10),KRS(10),RELAX(10),RSREF(10)     CAS14160
     5,RSSUM(10),ITITLE(10)                                             CAS14170
      COMMON                                                            CAS14180
     6/DC/CCHECK,DP,FLOWPC,FLOWST,FLOWUP,GREAT,ILINE,IPLRS,IPREF,IPRINT CAS14190
     6,ISTEP ,IX,IX1NY,IX1NY1,IX2NY2,IXMON,IXP1,IXPREF,IYMON,IYPREF     CAS14200
     6,JEMU,JH,JLAST,JLIM1,JLIM2,JLIM3,JLIM4,JP,JPP,JRHO                CAS14210
     6,JU,JV,JVP1,KINPRI,KMPA,KRAD,KRHOMU,KTEST,LABPHI                  CAS14220
     6,LASTEP,LINEF,LINEL,NEQ,NEQP1                                     CAS14230
     6,NODEF,NODEF1,NODEL,NODEL1,NODLP1,NTDMA,NUMCOL                    CAS14240
     6,NX,NXMAX,NXM1,NXM2,NXYG,NXYP,NXYU,NXYV                           CAS14250
     6,NY,NYMAX,NYM1,NYM2,PI,RSCHEK,RSMAX,TINY                          CAS14260
      COMMON/PROP/EMUREF,PRL(10),PRT(10),RHOREF                         CAS14270
      COMMON/D2D1/ARSL(22,10),RSLINE(22,10)                             CAS14280
      COMMON/D2D2/U(462),V(462),TKE(484),TED(484),H(484),PP(22),P(400)  CAS14290
     7,RHO(484),EMU(484)                                                CAS14300
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     7,INLY(10),IOUT(10),KIN,KOUT,RELTKE,RELTED,ISTCH                   CAS14310
      COMMON                                                            CAS14320
     9/TURB/C1,C2,CD,SQRTCD,CD25,ECONST,CTAUTW,CYPTW,TAUTW1(22)         CAS14330
     9,TAUTW2(22),YPUST1(22),YPUST2(22)                                 CAS14340
     9,TAULW(22),XPUSLW(22),CTAULW,CXPLW                                CAS14350
     9,GENK(22),FACTKE,FACTED,UTKE,UTED,CAPPA                           CAS14360
     9,INLY1,INLY2,IOUT1,IOUT2,I1M1,I2P1,I3M1,I4P1                      CAS14370
      COMMON/ABC/AREAE                                                  CAS14380
      DIMENSION F(3766)                                                 CAS14390
      DIMENSION DIFS(22),EMUS(22),HCONS(22),RHOS(22)                    CAS14400
      EQUIVALENCE (DIFS(2),DIFN(1)), (EMUS(2),EMUN(1))                  CAS14410
      EQUIVALENCE (RHOS(2),RHON(1)), (AREAE,AREAW)                      CAS14420
      EQUIVALENCE (HCONS(2),HCONN(1))                                   CAS14430
      EQUIVALENCE (F(1),U(1))                                           CAS14440
      DIMENSION A(22),B(22)                                             CAS14450
      EQUIVALENCE(A(1),AN(1)),(B(1),AS(1))                              CAS14460
CHAPTER 1  1  1  1  1  1     PRELIMINARIES    1  1  1  1  1  1  1       CAS14470
      GO TO(21,22),KRAD                                                 CAS14480
CHAPTER 2  2  2  2  2  2  2   RADII    2  2  2  2  2  2  2  2  2        CAS14490
21    DO 25 IY=1,NY                                                     CAS14500
25    R(IY)=1.                                                          CAS14510
      GO TO 23                                                          CAS14520
22    DO 26 IY=1,NY                                                     CAS14530
26    R(IY)=Y(IY)                                                       CAS14540
23    CONTINUE                                                          CAS14550
CHAPTER 3  3  3  3  3  3  3  CELL-NODE DISTANCES  3  3  3  3  3  3  3  CAS14560
C---------------------------------------- GRID-NODE DISTANCES           CAS14570
      DXG(1)=0.0                                                        CAS14580
      DYG(1)=0.0                                                        CAS14590
      DO 30 IX=2,NX                                                     CAS14600
      DXG(IX)=X(IX)-X(IX-1)                                             CAS14610
30    RDXG(IX)=1./DXG(IX)                                               CAS14620
      DO 31 IY=2,NY                                                     CAS14630
      DYG(IY)=Y(IY)-Y(IY-1)                                             CAS14640
31    RDYG(IY)=1./DYG(IY)                                               CAS14650
C--------------------------------------- U-NODE DISTANCES               CAS14660
      XU(1)=X(1)                                                        CAS14670
      DO 32 IX=2,NXM2                                                   CAS14680
32    XU(IX)=0.5*(X(IX)+X(IX+1))                                        CAS14690
      XU(NXM1)=X(NX)                                                    CAS14700
      XU(NX)=0.0                                                        CAS14710
      DXU(1)=0.0                                                        CAS14720
      DO 33 IX=2,NXM1                                                   CAS14730
      DXU(IX)=XU(IX)-XU(IX-1)                                           CAS14740
33    RDXU(IX)=1./DXU(IX)                                               CAS14750
      DXU(NX)=0.0                                                       CAS14760
C-------------------- V-NODE DISTANCES AND V-CELL BOUNDARY RADII        CAS14770
      YV(1)=Y(1)                                                        CAS14780
      RV(1)=R(1)                                                        CAS14790
      RVCB(1)=R(1)                                                      CAS14800
      DO 34 IY=2,NYM2                                                   CAS14810
      YV(IY)=0.5*(Y(IY)+Y(IY+1))                                        CAS14820
      RV(IY)=0.5*(R(IY)+R(IY+1))                                        CAS14830
34    RVCB(IY)=R(IY)                                                    CAS14840
      RVCB(2)=R(1)                                                      CAS14850
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      YV(NYM1)=Y(NY)                                                    CAS14860
      RV(NYM1)=R(NY)                                                    CAS14870
      RVCB(NYM1)=R(NY)                                                  CAS14880
      YV(NY)=0.0                                                        CAS14890
      RV(NY)=0.0                                                        CAS14900
      RVCB(NY)=0.0                                                      CAS14910
      DYV(1)=0.0                                                        CAS14920
      DO 35 IY=2,NYM1                                                   CAS14930
      DYV(IY)=YV(IY)-YV(IY-1)                                           CAS14940
35    RDYV(IY)=1./DYV(IY)                                               CAS14950
      DYV(NY)=0.0                                                       CAS14960
CHAPTER 4  4  4  4  4  4    CELL DIMENSIONS   4  4  4  4  4  4  4       CAS14970
C------------------------------------------- GRID-NODE CELLS            CAS14980
      SXG(1)=0.0                                                        CAS14990
      DO 40 IX=3,NXM2                                                   CAS15000
40    SXG(IX)=0.5*(DXG(IX)+DXG(IX+1))                                   CAS15010
      SXG(2)=DXG(2)+0.5*DXG(3)                                          CAS15020
      SXG(NXM1)=0.5*DXG(NXM1)+DXG(NX)                                   CAS15030
      SXG(NX)=0.0                                                       CAS15040
      SYG(1)=0.0                                                        CAS15050
      DO 41 IY=3,NYM2                                                   CAS15060
41    SYG(IY)=0.5*(DYG(IY)+DYG(IY+1))                                   CAS15070
      SYG(NY)=0.0                                                       CAS15080
      SYG(2)=DYG(2)+0.5*DYG(3)                                          CAS15090
      SYG(NYM1)=DYG(NY)+0.5*DYG(NYM1)                                   CAS15100
      DO 45 IX=2,NXM1                                                   CAS15110
45    RSXG(IX)=1./SXG(IX)                                               CAS15120
      DO 46 IY=2,NYM1                                                   CAS15130
46    RSYG(IY)=1./SYG(IY)                                               CAS15140
C------------------------------------------- U-VELOCITY CELLS           CAS15150
      SXU(1)=0.0                                                        CAS15160
      SXU(2)=X(3)-X(1)                                                  CAS15170
      NXM3=NX-3                                                         CAS15180
      DO 42 IX=3,NXM3                                                   CAS15190
42    SXU(IX)=X(IX+1)-X(IX)                                             CAS15200
      SXU(NXM2)=X(NX)-X(NXM2)                                           CAS15210
      SXU(NXM1)=0.0                                                     CAS15220
      SXU(NX)=0.0                                                       CAS15230
      DO 47 IX=2,NXM2                                                   CAS15240
47    RSXU(IX)=1./SXU(IX)                                               CAS15250
C------------------------------------------- V-VELOCITY CELLS           CAS15260
      SYV(1)=0.0                                                        CAS15270
      SYV(2)=Y(3)-Y(1)                                                  CAS15280
      NYM3=NY-3                                                         CAS15290
      DO 43 IY=3,NYM3                                                   CAS15300
43    SYV(IY)=Y(IY+1)-Y(IY)                                             CAS15310
      SYV(NYM2)=Y(NY)-Y(NYM2)                                           CAS1532[illegible]
      SYV(NYM1)=0.0                                                     CAS15330
      SYV(NY)=0.0                                                       CAS15340
      DO 48 IY=2,NYM2                                                   CAS15350
48    RSYV(IY)=1./SYV(IY)                                               CAS15360
CHAPTER 5  5  5  5  5  5   FACTORS FOR INTERPOLATING U AND V   5  5  5  CAS15370
      FU(1)=0.0                                                         CAS15380
      DO 50 IX=2,NXM1                                                   CAS15390
50    FU(IX)=(X(IX)-XU(IX-1))/(XU(IX)-XU(IX-1))                         CAS15400
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      FU(NX)=0.0                                                        CAS15410
      DO 52 IX=1,NX                                                     CAS15420
   52 FUNODE(IX)=FU(IX)                                                 CAS15430
      FV(1)=0.0                                                         CAS15440
      DO 51 IY=2,NYM1                                                   CAS15450
   51 FV(IY)=(Y(IY)-YV(IY-1))/(YV(IY)-YV(IY-1))                         CAS15460
      FV(NY)=0.0                                                        CAS15470
      DO 53 IY=1,NY                                                     CAS15480
   53 FVNODE(IY)=FV(IY)                                                 CAS15490
      FU(2)=0.0                                                         CAS15500
      FU(NXM1)=1.0                                                      CAS15510
      FV(2)=0.0                                                         CAS15520
      FV(NYM1)=1.0                                                      CAS15530
      RETURN                                                            CAS15540
      END                                                               CAS15550
      SUBROUTINE COEFF(LPHI)                                            CAS15560
      COMMON                                                            CAS15570
     1/CASE1/UINLET,FLOWIN,RPIPE,XPIPE,FXSTEP,HINLET,HWALL              CAS15580
     2/DNY/ DYG(22),DYV(22),FV(22),FVNODE(22),R(22),RDYG(22),RDYV(22)   CAS15590
     2,RSYG(22),RSYV(22),RV(22),RVCB(22),SYG(22),SYV(22),Y(22),YV(22)   CAS15600
     3/DNYONX/AE(22),AN(22),AP(22),AS(22),AW(22),C(22),D(22),DIFE(22)   CAS15610
     3,DIFN(22),DUW(22), DIFW(22),DU(22),DV(22),EMUE(22),EMUN(22)       CAS15620
     3       ,EMUW(22),HCONE(22),HCONN(22),          HCONW(22)          CAS15630
     3,PHIOLD(22),RHOE(22),RHON(22),        RHOW(22),SP(22),SU(22)      CAS15640
     3,VOLUME(22),CONN(22),CONS(22),CONE(22),CONW(22),ESMPHI(22)        CAS15650
     4/DNX/ DXG(22),DXU(22),FU(22),FUNODE(22),KOUNT(22),RDXG(22)        CAS15660
     4,RDXU(22),RSXG(22),RSXU(22),STORE(22),SXG(22),SXU(22),X(22),XU(22)CAS15670
     5/DJPHI/ IEW(10),ILAST(10),IMON(10),IXNY(10),IZERO(10)             CAS15680
     5,JGROUP(10),KADSOR(10),KSOLVE(10),KRS(10),RELAX(10),RSREF(10)     CAS15690
     5,RSSUM(10),ITITLE(10)                                             CAS15700
      COMMON                                                            CAS15710
     6/DO/CCHECK,DP,FLOWPC,FLOWST,FLOWUP,GREAT,ILINE,IPLRS,IPREF,IPRINT CAS15720
     6,ISTEP ,IX,IX1NY,IX1NY1,IX2NY2,IXMON,IXP1,IXPREF,IYMON,IYPREF     CAS15730
     6,JEMU,JH,JLAST,JLIM1,JLIM2,JLIM3,JLIM4,JP,JPP,JRHO                CAS15740
     6,JU,JV,JVP1,KINPRI,KMPA,KRAD,KRHOMU,KTEST,LABPHI                  CAS15750
     6,LASTEP,LINEF,LINEL,NEQ,NEOP1                                     CAS15760
     6,NODEF,NODEF1,NODEL,NODEL1,NODLP1,NTDMA,NUMCOL                    CAS15770
     6,NX,NXMAX,NXM1,NXM2,NXYG,NXYP,NXYU,NXYV                           CAS15780
     6,NY,NYMAX,NYM1,NYM2,PI,RSCHEK,RSMAX,TINY                          CAS15790
      COMMON/PROP/EMUREF,PRL(10),PRT(10),RHOREF                         CAS15800
      COMMON/D2D1/ARSL(22,10),RSLINE(22,10)                             CAS15810
      COMMON/D2D2/U(462),V(462),TKE(484),TED(484),H(484),PP(22),P(400)  CAS15820
     7,RHO(484),EMU(484)                                                CAS15830
     7,INLY(10),IOUT(10),KIN,KOUT,RELTKE,RELTED,ISTCH                   CAS15840
      COMMON                                                            CAS15850
     9/TURB/C1,C2,CD,SQRTCD,CD25,ECONST,CTAUTW,CYPTW,TAUTW1(22)         CAS15860
     9,TAUTW2(22),YPUST1(22),YPUST2(22)                                 CAS15870
     9,TAULW(22),XPUSLW(22),CTAULW,CXPLW                                CAS15880
     9,GENK(22),FACTKE,FACTED,JTKE,JTED,CAPPA                           CAS15890
     9,INLY1,INLY2,IOUT1,IOUT2,I1M1,I2P1,I3M1,I4P1                      CAS15900
      COMMON/ABC/AREAE                                                  CAS15910
      DIMENSION F(3766)                                                 CAS15920
      DIMENSION DIFS(22),EMUS(22),HCONS(22),RHOS(22)                    CAS15930
      EQUIVALENCE (DIFS(2),DIFN(1)), (EMUS(2),EMUN(1))                  CAS15940
      EQUIVALENCE (RHOS(2),RHON(1)), (AREAE,AREAW)                      CAS15950
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      EQUIVALENCE (HCONS(2),HCONN(1))                                   CAS15960
      EQUIVALENCE (F(1),U(1))                                           CAS15970
      DIMENSION A(22),B(22)                                             CAS15980
      EQUIVALENCE(A(1),AN(1)),(B(1),AS(1))                              CAS15990
CHAPTER 1  1  1  1  1    PRELIMINARIES    1  1  1  1  1  1  1  1  1  1  CAS16000
C--------------- DEFINE ARITHMETIC FUNCTION FOR COMBINING                CAS16010
C                APPROPRIATELY CONVECTION AND DIFFUSION CONTRIBUTIONS   CAS16020
C-------------------------------------------------------- HYBRID SCHEME CAS16030
C     CONDIF(DIFF,FCONV,CONV)=AMAX1(0., DIFF+FCONV,CONV)                CAS16040
C-------------------------------------------------------- UPWIND SCHEME CAS16050
      CONDIF(DIFF,FCONV,CONV)=AMAX1(DIFF,DIFF+CONV)                     CAS16060
      JPHI=LPHI                                                         CAS16070
      IF(KRAD.EQ.2) GO TO 12                                            CAS16080
      ASSIGN 1001 TO LG                                                 CAS16090
      ASSIGN 201 TO LU1                                                 CAS16100
      ASSIGN 211 TO LU2                                                 CAS16110
      ASSIGN 301 TO LV1                                                 CAS16120
      ASSIGN 311 TO LV2                                                 CAS16130
      ASSIGN 401 TO LP                                                  CAS16140
      GO TO 13                                                          CAS16150
12    ASSIGN 1002 TO LG                                                 CAS16160
      ASSIGN 202 TO LU1                                                 CAS16170
      ASSIGN 212 TO LU2                                                 CAS16180
      ASSIGN 302 TO LV1                                                 CAS16190
      ASSIGN 312 TO LV2                                                 CAS16200
      ASSIGN 402 TO LP                                                  CAS16210
13    IF(KSOLVE(JRHO).EQ.0) GO TO 120                                   CAS16220
C--------------------- CELL-WALL DENSITIES                              CAS16230
      IF(JPHI.GT.JVP1) GO TO 120                                        CAS16240
      IF(JPHI.EQ.JU) CALL CELPHI(JPHI,JRHO)                             CAS16250
      IF(JPHI.EQ.JV) CALL CELPHI(JPHI,JRHO)                             CAS16260
      IF(JPHI.EQ.JVP1) CALL CELPHI(JPHI,JRHO)                           CAS16270
C---------- TRANSFER DENSITIES STORED IN AN( ) TO RHON( ),ETC.          CAS16280
      N2=NODEL                                                          CAS16290
      IF(JPHI.EQ.JV) N2=NODEL1                                          CAS16300
      RHOS(NODEF)=AS(NODEF)                                             CAS16310
      DO 111  IY=NODEF,N2                                               CAS16320
      RHON(IY)=AN(IY)                                                   CAS16330
      RHOE(IY)=AE(IY)                                                   CAS16340
111   RHOW(IY)=AW(IY)                                                   CAS16350
120   IF(KSOLVE(JEMU).EQ.0) GO TO 130                                   CAS16360
C--------------------- CELL-WALL VISCOSITIES                            CAS16370
      IF(JPHI.GT.JVP1) GO TO 130                                        CAS16380
      IF(JPHI.EQ.JU) CALL CELPHI(JPHI,JEMU)                             CAS16390
      IF(JPHI.EQ.JV) CALL CELPHI(JPHI,JEMU)                             CAS16400
      IF(JPHI.EQ.JVP1 .AND. JPHI.NE.JPP) CALL CELPHI(JPHI,JEMU)         CAS16410
C---------- TRANSFER VISCOSITIES STORED IN AN( ) TO EMUN( ), ETC.       CAS16420
      N2=NODEL                                                          CAS16430
      IF(JPHI.EQ.JV) N2=NODEL1                                          CAS16440
      EMUS(NODEF)=AS(NODEF)                                             CAS16450
      DO 121  IY=NODEF,N2                                               CAS16460
      EMUN(IY)=AN(IY)                                                   CAS16470
      EMUE(IY)=AE(IY)                                                   CAS16480
121   EMUW(IY)=AW(IY)                                                   CAS16490
130   IF(JPP.EQ.JVP1) GO TO 140                                         CAS16500
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      IF(JPHI.NE.JVP1) GO TO 140                                        CAS16510
C---------------------- CONVECTION TERMS AND DIFFUSION-TERM*PRANDTL     CAS16520
C                       NUMBER FOR GENERAL PHI EQUATIONS                CAS16530
      SXGIX=SXG(IX)                                                     CAS16540
      AREA=SXG(IX)*RV(NODEF1)                                           CAS16550
      DIFS(NODEF)=EMUS(NODEF)*AREA*RDYG(NODEF)                          CAS16560
      ISV=NODEF1+IX1NY1                                                 CAS16570
      HCONS(NODEF)=0.5*RHOS(NODEF)*V(ISV)*AREA                          CAS16580
      RDXGIX=RDXG(IX)                                                   CAS16590
      RDXGI1=RDXG(IXP1)                                                 CAS16600
      DO 156 IY=NODEF,NODEL                                             CAS16610
      IYM1=IY-1                                                         CAS16620
      I=IY+IX1NY                                                        CAS16630
      IW=I-NY                                                           CAS16640
      IV=IY+IX1NY1                                                      CAS16650
      AREAN=SXGIX                                                       CAS16660
      AREAE=SYG(IY)                                                     CAS16670
      GO TO LG,(1001,1002)                                              CAS16680
1002  AREAN=AREAN*RV(IY)                                                CAS16690
      AREAE=AREAE*R(IY)                                                 CAS16700
C      AREAW=AREAE   , THROUGH EQUIVALENCE                              CAS16710
1001  VOLUME(IY)=AREAE*SXGIX                                            CAS16720
C      DIFS(IY)=DIFN(IYM1)      , THROUGH EQUIVALENCE                   CAS16730
      DIFN(IY)=EMUN(IY)*AREAN*RDYG(IY+1)                                CAS16740
      DIFE(IY)=EMUE(IY)*AREAE*RDXGI1                                    CAS16750
      DIFW(IY)=EMUW(IY)*AREAW*RDXGIX                                    CAS16760
C      HCONS(IY)=HCONN(IYM1)   , THROUGH EQUIVALENCE                    CAS16770
      HCONN(IY)=0.5*RHON(IY)*V(IV)*AREAN                                CAS16780
      HCONE(IY)=0.5*RHOE(IY)*U(I)*AREAE                                 CAS16790
      HCONW(IY)=0.5*RHOW(IY)*U(IW)*AREAW                                CAS16800
      CONN(IY)=HCONN(IY)+HCONN(IY)                                      CAS16810
      CONS(IY)=HCONS(IY)+HCONS(IY)                                      CAS16820
      CONE(IY)=HCONE(IY)+HCONE(IY)                                      CAS16830
      CONW(IY)=HCONW(IY)+HCONW(IY)                                      CAS16840
      ESMPHI(IY)=CONS(IY)-CONN(IY)+CONW(IY)-CONE(IY)                    CAS16850
156   ESMPHI(IY)=AMAX1(0.0,  -ESMPHI(IY))                               CAS16860
140   IF(JPHI.EQ.JU) GO TO 20                                           CAS16870
      IF(JPHI.EQ.JV) GO TO 30                                           CAS16880
      IF(JPHI.EQ.JPP) GO TO 40                                          CAS16890
      GO TO 50                                                          CAS16900
CHAPTER 2  2  2  2  2    COEFFICIENTS FOR U-EQUATION    2  2  2  2  2   CAS16910
C---------------------- FOR Y-DIRECTION TDMA TRAVERSES                  CAS16920
C  CALCULATE DIFFUSION AND CONVECTION COEFFICIENTS FOR SOUTH BOUNDARY   CAS16930
C   OF BOTTOM CELL                                                      CAS16940
20    AREA=SXU(IX)*RV(NODEF1)                                           CAS16950
      DN=EMUS(NODEF)*AREA*RDYG(NODEF)                                   CAS16960
      ISV=NODEF1+IX1NY1                                                 CAS16970
      ISEV=ISV+NYM1                                                     CAS16980
      HCN=0.25*RHOS(NODEF)*(V(ISV)+V(ISEV))*AREA                        CAS16990
C---------------------- COEFFICIENTS FOR ALL CELLS ON THE STRIP         CAS17000
      FUIX=FU(IX)                                                       CAS17010
      OMFUIX=1.-FUIX                                                    CAS17020
      FUIXP1=FU(IXP1)                                                   CAS17030
      SXUIX=SXU(IX)                                                     CAS17040
      RDXUIX=RDXU(IX)                                                   CAS17050
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      RDXUI1=RDXU(IXP1)
      RSXUIX=RSXU(IX)
C     SET DU(IY)
      IF(IX.NE.2) GO TO 281
      DO 280 IY=NODEF,NODEL
  280 DU(IY)=0.0
  281 CONTINUE
      DO 285 IY=NODEF,NODEL
  285 DUW(IY)=DU(IY)
      ASSIGN 27 TO NGOTO
      IF(KRHOMU.NE.0) GO TO 28
      ASSIGN 25 TO NGOTO
28    DO 26 IY=NODEF,NODEL
      I=IY+IX1NY
      IE=I+NY
      IW=I-NY
      IV=IY+IX1NY1
      IEV=IV+NYM1
      ISV=IV-1
      ISEV=IEV-1
      IP=IY-1+IX2NY2
      IEP=IP+NYM2
      IYP1=IY+1
      AREAN=SXUIX
      AREAE=SYG(IY)
      GO TO LU1,(201,202)
202   AREAN=AREAN*RV(IY)
      AREAE=AREAE*R(IY)
C      AREAW=AREAE   , THROUGH EQUIVALENCE
201   VOLUME(IY)=AREAE*SXUIX
      DS=DN
      DN=EMUN(IY)*AREAN*RDYG(IYP1)
      DE=EMUE(IY)*AREAE*RDXU(IXP1)
      DW=EMUW(IY)*AREAW*RDXUIX
      HCS=HCN
      HCN=RHON(IY)*0.25*(V(IV)+V(IEV))*AREAN
      CN=HCN+HCN
      CS=HCS+HCS
      CE=RHOE(IY)*AREAE*(U(I)+(U(IE)-U(I))*FUIXP1)
      CW=RHOW(IY)*AREAW*(U(IW)+(U(I)-U(IW))*FUIX)
      FCE=FUIXP1*CE
      FCW=OMFUIX*CW
C---------------------- ERROR SOURCE OF MASS
      ESMASS=CS-CN+CW-CE
      FM=AMAX1(0.0,-ESMASS)
C----------------- COMBINING DIFFUSION AND CONVECTION CONTRIBUTIONS
      AN(IY)=CONDIF(DN,-HCN,-CN)
      AS(IY)=CONDIF(DS, HCS, CS)
      AE(IY)=CONDIF(DE,-FCE,-CE)
      AW(IY)=CONDIF(DW, FCW, CW)
C---------------------- SOURCE TERMS
      DU(IY)=AREAE
      SU(IY)=FM*U(I)+DU(IY)*(P(IP)-P(IEP))
      SP(IY)=-FM
      GO TO NGOTO, (25,27)
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 27   DUDXW=(U(I)-U(IW))*RDXUIX                                          CAS17610
      DUDXE=(U(IE)-U(I))*RDXUI1                                          CAS17620
      STERM=(EMUE(IY)*DUDXE-EMUW(IY)*DUDXW)*RSXUIX                       CAS17630
      DVDXN=(V(IEV)-V(IV))*RSXUIX                                        CAS17640
      DVDXS=(V(ISEV)-V(ISV))*RSXUIX                                      CAS17650
      GO TO LU2,(211,212)                                                CAS17660
 211  STERM=STERM+(EMUN(IY)*DVDXN-EMUS(IY)*DVDXS)/AREAE                  CAS17670
      GO TO 213                                                          CAS17680
 212  STERM=STERM+(EMUN(IY)*RV(IY)*DVDXN-EMUS(IY)*RV(IY-1)*DVDXS)/AREAE  CAS17690
 213  SU(IY)=SU(IY)+STERM*VOLUME(IY)                                     CAS17700
C---------------------- STORE U IN PHIOLD                                CAS17710
 25   PHIOLD(IY)=U(I)                                                    CAS17720
 26   CONTINUE                                                           CAS17730
C---------------------- PUT BOUNDARY END VALUES IN PHIOLD                CAS17740
      I1=NODEF1+IX1NY                                                    CAS17750
      I2=NODLP1+IX1NY                                                    CAS17760
      PHIOLD(NODEF1)=U(I1)                                               CAS17770
      PHIOLD(NODLP1)=U(I2)                                               CAS17780
C---------------------- ADDITIONAL SOURCE TERMS IF REQUIRED              CAS17790
      IF(KADSOR(JU).NE.0) CALL SOURCE(JU)                                CAS17800
      RETURN                                                             CAS17810
CHAPTER 3  3  3  3  3   COEFFICIENTS FOR V-EQUATION    3  3  3  3  3     CAS17820
C---------------------- FOR Y-DIRECTION TDMA TRAVERSES                   CAS17830
C  CALCULATE DIFFUSION AND CONVECTION COEFFICIENTS FOR SOUTH BOUNDARY    CAS17840
C   OF BOTTOM CELL                                                       CAS17850
 30   AREA=SXG(IX)*RV(NODEF1)                                            CAS17860
      ISV=NODEF1+IX1NY1                                                  CAS17870
      DN=EMUS(NODEF)*AREA*RDYV(NODEF)                                    CAS17880
      CN=RHOS(NODEF)*V(ISV)*AREA                                         CAS17890
C---------------------- COEFFICIENTS FOR ALL CELLS ON THE STRIP           CAS17900
      SXGIX=SXG(IX)                                                      CAS17910
      RDXGIX=RDXG(IX)                                                    CAS17920
      RDXGI1=RDXG(IXP1)                                                  CAS17930
      RSXGIX=RSXG(IX)                                                    CAS17940
      ASSIGN 38 TO NGOTO                                                 CAS17950
      IF(KRHOMU.NE.0) GO TO 34                                           CAS17960
      ASSIGN 37 TO NGOTO                                                 CAS17970
 34   DO 36 IY=NODEF,NODEL1                                              CAS17980
      I=IY+IX1NY                                                         CAS17990
      IN=I+1                                                             CAS18000
      IW=I-NY                                                            CAS18010
      INW=IW+1                                                           CAS18020
      IV=IY+IX1NY1                                                       CAS18030
      INV=IV+1                                                           CAS18040
      ISV=IV-1                                                           CAS18050
      IP=IY-1+IX2NY2                                                     CAS18060
      INP=IP+1                                                           CAS18070
      IYP1=IY+1                                                          CAS18080
      AREAN=SXGIX                                                        CAS18090
      AREAE=SYV(IY)                                                      CAS18100
      GO TO LV1,(301,302)                                                CAS18110
 302  AREAN=AREAN*RVCB(IYP1)                                             CAS18120
      AREAE=AREAE*RV(IY)                                                 CAS18130
C      AREAW=AREAE   , THROUGH EQUIVALENCE                               CAS18140
 301  VOLUME(IY)=AREAE*SXGIX                                             CAS18150
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      DS=DN                                                             CAS18160
      DN=EMUN(IY)*AREAN*RDYV(IYP1)                                      CAS18170
      DE=EMUE(IY)*AREAE*RDXGI1                                          CAS18180
      DW=EMUW(IY)*AREAW*RDXGIX                                          CAS18190
      CS=CN                                                             CAS18200
      VN=V(IV)+(V(INV)-V(IV))*FV(IYP1)                                  CAS18210
      CN=RHON(IY)*VN*AREAN                                              CAS18220
      FCS=(1.-FV(IY))*CS                                                CAS18230
      FCN=FV(IYP1)*CN                                                   CAS18240
      HCE=0.25*RHOE(IY)*(U(I)+U(IN))*AREAE                              CAS18250
      HCW=0.25*RHOW(IY)*(U(INW)+U(IW))*AREAW                            CAS18260
      CE=HCE+HCE                                                        CAS18270
      CW=HCW+HCW                                                        CAS18280
C----------------------- CALCULATE ERROR SOURCE OF MASS                 CAS18290
      ESMASS=CS-CN+CW-CE                                                CAS18300
      FM=AMAX1(0.0,-ESMASS)                                             CAS18310
C------------- COMBINING DIFFUSION AND CONVECTION CONTRIBUTIONS         CAS18320
      AN(IY)=CONDIF(DN,-FCN,-CN)                                        CAS18330
      AS(IY)=CONDIF(DS, FCS, CS)                                        CAS18340
      AE(IY)=CONDIF(DE,-HCE,-CE)                                        CAS18350
      AW(IY)=CONDIF(DW, HCW, CW)                                        CAS18360
C---------------- SOURCE TERMS                                          CAS18370
      DV(IY)=VOLUME(IY)*RSYV(IY)                                        CAS18380
      SU(IY)=FM*V(IV)+DV(IY)*(P(IP)-P(INP))                             CAS18390
      SP(IY)=-FM                                                        CAS18400
      GO TO NGOTO, (37,38)                                              CAS18410
37    STERM=0.0                                                         CAS18420
      IF(KRAD.EQ.2) STERM=STERM-0.5*(EMUN(IY)+EMUS(IY))*V(IV)/RV(IY)**2 CAS18430
      GO TO 313                                                         CAS18440
38    DUDYE=(U(IN)-U(I))*RSYV(IY)                                       CAS18450
      DUDYW=(U(INW)-U(IW))*RSYV(IY)                                     CAS18460
      STERM=(EMUE(IY)*DUDYE-EMUW(IY)*DUDYW)*RSXGIX                      CAS18470
      DVDYN=(V(INV)-V(IV))*RDYV(IYP1)                                   CAS18480
      DVDYS=(V(IV)-V(ISV))*RDYV(IY)                                     CAS18490
      GO TO LV2,(311,312)                                               CAS18500
311   STERM=STERM+(EMUN(IY)*DVDYN-EMUS(IY)*DVDYS)/AREAE                 CAS18510
      GO TO 313                                                         CAS18520
312   STERM=STERM+(EMUN(IY)*R(IYP1)*DVDYN-EMUS(IY)*R(IY)*DVDYS)/AREAE   CAS18530
      STERM=STERM-(EMUN(IY)+EMUS(IY))*V(IV)/RV(IY)**2                   CAS18540
313   SU(IY)=SU(IY)+STERM*VOLUME(IY)                                    CAS18550
C----------------------- STORE V IN PHIOLD                              CAS18560
      PHIOLD(IY)=V(IV)                                                  CAS18570
36    CONTINUE                                                          CAS18580
C----------------------- PUT BOUNDARY END VALUES IN PHIOLD              CAS18590
      IV1=NODEF1+IX1NY1                                                 CAS18600
      PHIOLD(NODEF1)=V(IV1)                                             CAS18610
      IV=NODEL+1+IX1NY1                                                 CAS18620
      PHIOLD(NODEL)=V(IV)                                               CAS18630
C----------------------- ADDITIONAL SOURCE TERMS IF REQUIRED            CAS18640
      IF(KADSOR(JV).NE.0) CALL SOURCE(JV)                               CAS18650
      RETURN                                                            CAS18660
CHAPTER 4  4  4  4  4   COEFFICIENTS FOR PRESSURE-CORRECTION EQUSTION   CAS18670
C----------------------- FOR Y-DIRECTION TDMA TRAVERSES                 CAS18680
40    SXGIX=SXG(IX)                                                     CAS18690
      DO 46 IY=NODEF,NODEL                                              CAS18700
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      I=IY+IX1NY                                                        CAS18710
      IW=I-NY                                                           CAS18720
      IV=IY+IX1NY1                                                      CAS18730
      ISV=IV-1                                                          CAS18740
      ARHON=SXGIX*RHON(IY)                                              CAS18750
      ARHOS=SXGIX*RHOS(IY)                                              CAS18760
      ARHOE=SYG(IY)*RHOE(IY)                                            CAS18770
      ARHOW=SYG(IY)*RHOW(IY)                                            CAS18780
      IYM1=IY-1                                                         CAS18790
      GO TO LP,(401,402)                                                CAS18800
402   ARHON=ARHON*RV(IY)                                                CAS18810
      ARHOS=ARHOS*RV(IYM1)                                              CAS18820
      ARHOE=ARHOE*R(IY)                                                 CAS18830
      ARHOW=ARHOW*R(IY)                                                 CAS18840
401   AN(IY)=ARHON*DV(IY)                                               CAS18850
      AS(IY)=ARHOS*DV(IYM1)                                             CAS18860
      AE(IY)=ARHOE*DU(IY)                                               CAS18870
      AW(IY)=ARHOW*DUW(IY)                                              CAS18880
C---------------------- CALCULATE ERROR SOURCE OF MASS                  CAS18890
      ESMASS=-ARHON*V(IV)+ARHOS*V(ISV)-ARHOE*U(I)+ARHOW*U(IW)           CAS18900
      RSLINE(IX,JPP)=RSLINE(IX,JPP)+ESMASS                              CAS18910
C---------------------- SOURCE TERMS                                    CAS18920
      SU(IY)=ESMASS                                                     CAS18930
      SP(IY)=0.0                                                        CAS18940
C---------------------- SET PHIOLD TO ZERO                              CAS18950
      PHIOLD(IY)=0.0                                                    CAS18960
46    CONTINUE                                                          CAS18970
C---------------------- PUT BOUNDARY END VALUES IN PHIOLD               CAS18980
      PHIOLD(NODEF1)=0.0                                                CAS18990
      PHIOLD(NODLP1)=0.0                                                CAS19000
C---------------------- ADDITIONAL SOURCE TERMS IF REQUIRED             CAS19010
      IF(KADSOR(JPP).NE.0) CALL SOURCE(JPP)                             CAS19020
      RETURN                                                            CAS19030
CHAPTER 5  5  5  5  5    PHI EQUATION    5  5  5  5  5  5  5  5  5  5   CAS19040
50    RPRT=1./PRT(JPHI)                                                 CAS19050
C---------------------- COEFFICIENTS FOR ALL CELLS ON THE STRIP         CAS19060
      ICONST=IXNY(JPHI)+IZERO(JPHI)                                     CAS19070
      IEWPHI=IEW(JPHI)                                                  CAS19080
      DO 56 IY=NODEF,NODEL                                              CAS19090
      I=IY+ICONST                                                       CAS19100
      IE=I+IEWPHI                                                       CAS19110
      IW=I-IEWPHI                                                       CAS19120
      DS=DIFS(IY)*RPRT                                                  CAS19130
      DN=DIFN(IY)*RPRT                                                  CAS19140
      DE=DIFE(IY)*RPRT                                                  CAS19150
      DW=DIFW(IY)*RPRT                                                  CAS19160
C---------------------- ERROR SOURCE OF MASS                            CAS19170
      FM=ESMPHI(IY)                                                     CAS19180
C----------------- COMBINING DIFFUSION AND CONVECTION CONTRIBUTIONS     CAS19190
      AN(IY)=CONDIF(DN,-HCONN(IY),-CONN(IY))                            CAS19200
      AS(IY)=CONDIF(DS, HCONS(IY), CONS(IY))                            CAS19210
      AE(IY)=CONDIF(DE,-HCONE(IY),-CONE(IY))                            CAS19220
      AW(IY)=CONDIF(DW, HCONW(IY), CONW(IY))                            CAS19230
      PHIOLD(IY)=F(I)                                                   CAS19240
C---------------------- STORING PHI IN PHIOLD                           CAS19250
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C----------------------- SOURCE TERMS                                   CAS19260
      SU(IY)=FM*PHIOLD(IY)                                              CAS19270
      SP(IY)=-FM                                                        CAS19280
56    CONTINUE                                                          CAS19290
C----------------------- PUT BOUNDARY END VALUES IN PHIOLD              CAS19300
      I1=NODEF-1+ICONST                                                 CAS19310
      IL=NODEL+1+ICONST                                                 CAS19320
      PHIOLD(NODEF1)=F(I1)                                              CAS19330
      PHIOLD(NODLP1)=F(IL)                                              CAS19340
C----------------------- ADDITIONAL SOURCE TERMS IF REQUIRED            CAS19350
      IF(KADSOR(JPHI).NE.0) CALL SOURCE(JPHI)                           CAS19360
      RETURN                                                            CAS19370
      END                                                               CAS19380
      SUBROUTINE CELPHI(JCELL,LPHI)                                     CAS19390
      COMMON                                                            CAS19400
     1/CASE1/UINLET,FLOWIN,RPIPE,XPIPE,FXSTEP,HINLET,HWALL              CAS19410
     2/DNY/ DYG(22),DYV(22),FV(22),FVNODE(22),R(22),RDYG(22),RDYV(22)   CAS19420
     2,RSYG(22),RSYV(22),RV(22),RVCB(22),SYG(22),SYV(22),Y(22),YV(22)   CAS19430
     3/DNYONX/AE(22),AN(22),AP(22),AS(22),AW(22),C(22),D(22),DIFE(22)   CAS19440
     3,DIFN(22),DUW(22), DIFW(22),DU(22),DV(22),EMUE(22),EMUN(22)       CAS19450
     3         ,EMUW(22),HCONE(22),HCONN(22),          HCONW(22)        CAS19460
     3,PHIOLD(22),RHOE(22),RHON(22),        RHOW(22),SP(22),SU(22)      CAS19470
     3,VOLUME(22),CONN(22),CONS(22),CONE(22),CONW(22),ESMPHI(22)        CAS19480
     4/DNX/ DXG(22),DXU(22),FU(22),FUNODE(22),KOUNT(22),RDXG(22)        CAS19490
     4,RDXU(22),RSXG(22),RSXU(22),STORE(22),SXG(22),SXU(22),X(22),XU(22)CAS19500
     5/DUPHI/ IEW(10),ILAST(10),IMON(10),IXNY(10),IZERO(10)             CAS19510
     5,JGROUP(10),KADSOR(10),KSOLVE(10),KRS(10),RELAX(10),RSREF(10)     CAS19520
     5,RSSUM(10),ITITLE(10)                                             CAS19530
      COMMON                                                            CAS19540
     6/DO/CCHECK,DP,FLOWPC,FLOWST,FLOWUP,GREAT,ILINE,IPLRS,IPREF,IPRINT CAS19550
     6,ISTEP ,IX,IX1NY,IX1NY1,IX2NY2,IXMON,IXP1,IXPREF,IYMON,IYPREF     CAS19560
     6,JEMU,JH,JLAST,JLIM1,JLIM2,JLIM3,JLIM4,JP,JPP,JRHO                CAS19570
     6,JU,JV,JVP1,KINPRI,KMPA,KRAD,KRHOMU,KTEST,LABPHI                  CAS19580
     6,LASTEP,LINEF,LINEL,NEQ,NEQP1                                     CAS19590
     6,NODEF,NODEF1,NODEL,NODEL1,NODLP1,NTDMA,NUMCOL                    CAS19600
     6,NX,NXMAX,NXM1,NXY2,NXYG,NXYP,NXYU,NXYV                           CAS19610
     6,NY,NYMAX,NYM1,NYM2,PI,RSCHEK,RSMAX,TINY                          CAS19620
      COMMON/PROP/EMUREF,PRL(10),PRT(10),RHOREF                         CAS19630
      COMMON/D2D1/ARSL(22,10),RSLINE(22,10)                             CAS19640
      COMMON/D2D2/U(462),V(462),TKE(484),TED(484),H(484),PP(22),P(400)  CAS19650
     7,RHO(484),EMU(484)                                                CAS19660
     7,INLY(10),IOUT(10),KIN,KOUT,RELTKE,RELTED,ISTCH                   CAS19670
      COMMON                                                            CAS19680
     9/TURB/C1,C2,CD,SQRTCD,CD25,ECONST,CTAUTW,CYPTW,TAUTW1(22)         CAS19690
     9,TAUTW2(22),YPUST1(22),YPUST2(22)                                 CAS19700
     9,TAULW(22),XPUSLW(22),CTAULW,CXPLW                                CAS19710
     9,GENK(22),FACTKE,FACTED,JTKE,JTED,CAPPA                           CAS19720
     9,INLY1,INLY2,IOUT1,IOUT2,I1M1,I2P1,I3M1,I4P1                      CAS19730
      COMMON/ABC/AREAE                                                  CAS19740
      DIMENSION F(3766)                                                 CAS19750
      DIMENSION DIFS(22),EMUS(22),HCONS(22),RHOS(22)                    CAS19760
      EQUIVALENCE (DIFS(2),DIFN(1)), (EMUS(2),EMUN(1))                  CAS19770
      EQUIVALENCE (RHOS(2),RHON(1)), (AREAE,AREAW)                      CAS19780
      EQUIVALENCE (HCONS(2),HCONN(1))                                   CAS19790
      EQUIVALENCE (F(1),U(1))                                           CAS19800
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      DIMENSION A(22),B(22)                                             CAS19810
      EQUIVALENCE(A(1),AN(1)),(B(1),AS(1))                              CAS19820
      JPHI=LPHI                                                         CAS19830
      IF(JCELL.EQ.JU) GO TO 10                                          CAS19840
      IF(JCELL.EQ.JV) GO TO 20                                          CAS19850
      GO TO 30                                                          CAS19860
C----------------------- CELL-WALL PROPERTIES FOR U-CELLS               CAS19870
10    CONTINUE                                                          CAS19880
COMMENT...AE,AW,AN,AS ARE USED AS TEMPORARY STORAGES, VALUES THERE      CAS19890
COMMENT...SHOULD BE APPROPRIATELY TRANSFERRED IN THE CALLING SUBROUTINE CAS19900
C----------------------- INDICES TO ACCOUNT FOR EFFECTS OF ENDS         CAS19910
C-----------------------    BOUNDARIES (EAST AND WEST)                  CAS19920
      LE=0                                                              CAS19930
      LW=0                                                              CAS19940
      IF(IX.EQ.2) LW=NY                                                 CAS19950
      IF(IX.EQ.NXM2) LE=NY                                              CAS19960
C----------------------- EAST AND WEST WALLS                            CAS19970
      ICONST=IX1NY+IZERO(JPHI)-LW                                       CAS19980
      NYLE=NY+LE                                                        CAS19990
      DO 11 IY=NODEF,NODEL                                              CAS20000
      I=IY+ICONST                                                       CAS20010
      IE=I+NYLE                                                         CAS20020
      AW(IY)=F(I)                                                       CAS20030
11    AE(IY)=F(IE)                                                      CAS20040
C----------------------- NORTH AND SOUTH WALLS                          CAS20050
      I=NODEF1+ICONST                                                   CAS20060
      IE=I+NYLE                                                         CAS20070
      AS(NODEF)=0.5*(F(I)+F(IE))                                        CAS20080
      IF(NODEF.GT.2) AS(NODEF)=0.25*(AE(NODEF)+AW(NODEF))+0.5*AS(NODEF) CAS20090
      DO 12 IY=NODEF,NODEL1                                             CAS20100
      IYP1=IY+1                                                         CAS20110
12    AN(IY)=0.25*(AE(IY)+AW(IY)+AE(IYP1)+AW(IYP1))                     CAS20120
C----------------------- AN FOR LAST CELL                               CAS20130
      IN=NODEL+1+ICONST                                                 CAS20140
      INE=IN+NYLE                                                       CAS20150
      AN(NODEL)=0.5*(F(IN)+F(INE))                                      CAS20160
      IF(NODEL.LT.NYM1) AN(NODEL)=0.25*(F(IN-1)+F(INE-1))+0.5*AN(NODEL) CAS20170
      RETURN                                                            CAS20180
C----------------------- CELL-WALL PROPERTIES FOR V-CELLS               CAS20190
20    CONTINUE                                                          CAS20200
COMMENT...AE,AW,AN,AS ARE USED AS TEMPORARY STORAGES, VALUES THERE      CAS20210
COMMENT...SHOULD BE APPROPRIATELY TRANSFERRED IN THE CALLING SUBROUTINE CAS20220
C----------------------- FACTORS TO ACCOUNT FOR EFFECTS OF END          CAS20230
C----------------------- BOUNDARIES (EAST AND WEST)                     CAS20240
      BWW=0.25                                                          CAS20250
      BEW=0.25                                                          CAS20260
      IF(IX.EQ.2) BWW=0.5                                               CAS20270
      IF(IX.EQ.NXM1) BEW=0.0                                            CAS20280
      BWE=0.5-BWW                                                       CAS20290
      BEE=0.5-BEW                                                       CAS20300
C----------------------- EAST AND WEST WALLS                            CAS20310
      ICONST=IX1NY+IZERO(JPHI)                                          CAS20320
      DO 21 IY=NODEF,NODEL1                                             CAS20330
      I=IY+ICONST                                                       CAS20340
      IN=I+1                                                            CAS20350
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      IW=I-NY                                                           CAS20360
      INW=IW+1                                                          CAS20370
      IE=I+NY                                                           CAS20380
      INE=IE+1                                                          CAS20390
      FPN=F(I)+F(IN)                                                    CAS20400
      AW(IY)=BWW*(F(IW)+F(INW))+BWE*FPN                                 CAS20410
21    AE(IY)=BEW*FPN+BEE*(F(IE)+F(INE))                                 CAS20420
C---------------------- NORTH AND SOUTH WALLS                           CAS20430
      I=NODEF1+ICONST                                                   CAS20440
      AS(NODEF)=F(I)                                                    CAS20450
      IF(NODEF.GT.2) AS(NODEF)=F(I+1)                                   CAS20460
      N2=NODEL1-1                                                       CAS20470
      ICONST=1+IX1NY+IZERO(JPHI)                                        CAS20480
      DO 22 IY=NODEF,N2                                                 CAS20490
      IN=IY+ICONST                                                      CAS20500
22    AN(IY)=F(IN)                                                      CAS20510
C---------------------- AN FOR LAST CELL                                CAS20520
      INN=NODEL+ICONST                                                  CAS20530
      AN(NODEL1)=F(INN)                                                 CAS20540
      IF(NODEL1.LT.NYM2) AN(NODEL1)=F(INN-1)                            CAS20550
      RETURN                                                            CAS20560
C---------------------- CELL-WALL PROPERTIES FOR G-CELL                 CAS20570
30    CONTINUE                                                          CAS20580
COMMENT...AE,AW,AN,AS ARE USED AS TEMPORARY STORAGES, VALUES THERE      CAS20590
COMMENT...SHOULD BE APPROPRIATELY TRANSFERRED IN THE CALLING SUBROUTINE CAS20600
C---------------------- FACTORS TO ACCOUNT FOR EFFECTS OF END           CAS20610
C---------------------- BOUNDARIES (EAST AND WEST)                      CAS20620
      BWW=0.5                                                           CAS20630
      BEW=0.5                                                           CAS20640
      IF(IX.EQ.2) BWW=1.                                                CAS20650
      IF(IX.EQ.NXM1) BEW=0.                                             CAS20660
      BWE=1.-BWW                                                        CAS20670
      BEE=1.-BEW                                                        CAS20680
C---------------------- ALL FOUR CELL WALLS                             CAS20690
      ICONST=IX1NY+IZERO(JPHI)                                          CAS20700
      I=NODEF1+ICONST                                                   CAS20710
      AS(NODEF)=F(I)                                                    CAS20720
      IF(NODEF.GT.2) AS(NODEF)=0.5*(F(I)+F(I+1))                        CAS20730
      DO 31 IY=NODEF,NODEL                                              CAS20740
      I=IY+ICONST                                                       CAS20750
      IN=I+1                                                            CAS20760
      IE=I+NY                                                           CAS20770
      IW=I-NY                                                           CAS20780
      AN(IY)=0.5*(F(I)+F(IN))                                           CAS20790
      AW(IY)=BWW*F(IW)+BWE*F(I)                                         CAS20800
31    AE(IY)=BEW*F(I)+BEE*F(IE)                                         CAS20810
      IF(NODEL.LT.NYM1) RETURN                                          CAS20820
C---------------------- CORRECT AN FOR THE LAST CELL                    CAS20830
      IN=NODEL+ICONST                                                   CAS20840
      AN(NODEL)=F(IN)                                                   CAS20850
      RETURN                                                            CAS20860
      END                                                               CAS20870
      SUBROUTINE SOLVE(LPHI)                                            CAS20880
      COMMON                                                            CAS20890
     1/CASE1/UINLET,FLOWIN,RPIPE,XPIPE,FXSTEP,HINLET,HWALL              CAS20900
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     2/DNY/ DYG(22),DYV(22),FV(22),FVNODE(22),R(22),RDYG(22),RDYV(22)   CAS20910
     2,RSYG(22),RSYV(22),RV(22),RVCB(22),SYG(22),SYV(22),Y(22),YV(22)   CAS20920
     3/DNYONX/AE(22),AN(22),AP(22),AS(22),AW(22),C(22),D(22),DIFE(22)   CAS20930
     3,DIFN(22),DUW(22), DIFW(22),DU(22),DV(22),EMUE(22),EMUN(22)       CAS20940
     3         ,EMUW(22),HCONE(22),HCONN(22),          HCONW(22)        CAS20950
     3,PHIOLD(22),RHOE(22),RHON(22),        RHOW(22),SP(22),SU(22)      CAS20960
     3,VOLUME(22),CONN(22),CONS(22),CONE(22),CONW(22),ESMPHI(22)        CAS20970
     4/DNX/ DXG(22),DXU(22),FU(22),FUNODE(22),KOUNT(22),RDXG(22)        CAS20980
     4,RDXU(22),RSXG(22),RSXU(22),STORE(22),SXG(22),SXU(22),X(22),XU(22)CAS20990
     5/DJPHI/ IEW(10),ILAST(10),IMON(10),IXNY(10),IZERO(10)             CAS21000
     5,JGROUP(10),KADSOR(10),KSOLVE(10),KRS(10),RELAX(10),RSREF(10)     CAS21010
     5,PSSUM(10),ITITLE(10)                                             CAS21020
      COMMON                                                            CAS21030
     6/CO/CCHECK,DP,FLOWPC,FLOWST,FLOWUP,GREAT,ILINE,IPLRS,IPREF,IPRINT CAS21040
     6,ISTEP ,IX,IX1NY,IX1NY1,IX2NY2,IXMON,IXP1,IXPREF,IYMON,IYPREF     CAS21050
     6,JEMU,JH,JLAST,JLIM1,JLIM2,JLIM3,JLIM4,JP,JPP,JRHO                CAS21060
     6,JU,JV,JVP1,KINPRI,KMPA,KRAD,KRHOMU,KTEST,LABPHI                  CAS21070
     6,LASTEP,LINEF,LINEL,NEQ,NEQP1                                     CAS21080
     6,NODEF,NODEF1,NODEL,NODEL1,NODLP1,NTDMA,NUMCOL                    CAS21090
     6,NX,NXMAX,NXM1,NXM2,NXYG,NXYP,NXYU,NXYV                           CAS21100
     6,NY,NYMAX,NYM1,NYM2,PI,RSCHEK,RSMAX,TINY                          CAS21110
      COMMON/PROP/EMUREF,PRL(10),PRT(10),RHOREF                         CAS21120
      COMMON/D2D1/ARSL(22,10),RSLINE(22,10)                             CAS21130
      COMMON/D2D2/U(462),V(462),TKE(484),TED(484),H(484),PP(22),P(400)  CAS21140
     7,RHO(484),EMU(484)                                                CAS21150
     7,INLY(10),IOUT(10),KIN,KOUT,RELTKE,RELTED,ISTCH                   CAS21160
      COMMON                                                            CAS21170
     9/TURB/C1,C2,CD,SQRTCD,CD25,ECONST,CTAUTW,CYPTW,TAUTW1(22)         CAS21180
     9,TAUTW2(22),YPUST1(22),YPUST2(22)                                 CAS21190
     9,TAULW(22),XPUSLW(22),CTAULW,CXPLW                                CAS21200
     9,GENK(22),FACTKE,FACTED,JTKE,JTED,CAPPA                           CAS21210
     9,INLY1,INLY2,IOUT1,IOUT2,I1M1,I2P1,I3M1,I4P1                      CAS21220
      COMMON/ABC/AREAE                                                  CAS21230
      DIMENSION F(3766)                                                 CAS21240
      DIMENSION DIFS(22),EMUS(22),HCONS(22),RHOS(22)                    CAS21250
      EQUIVALENCE (DIFS(2),DIFN(1)), (EMUS(2),EMUN(1))                  CAS21260
      EQUIVALENCE (RHOS(2),RHON(1)), (AREAE,AREAW)                      CAS21270
      EQUIVALENCE (HCONS(2),HCONN(1))                                   CAS21280
      EQUIVALENCE (F(1),U(1))                                           CAS21290
      DIMENSION A(22),B(22)                                             CAS21300
      EQUIVALENCE(A(1),AN(1)),(B(1),AS(1))                              CAS21310
COMMENT...... A AND B HAVE BEEN MADE EQUIVALENT TO AN, AS RESPECTIVELY  CAS21320
      JPHI=LPHI                                                         CAS21330
      RRELAX=1./RELAX(JPHI)                                             CAS21340
      RELAX1=1.-RELAX(JPHI)                                             CAS21350
      KRSPHI=KRS(JPHI)                                                  CAS21360
      ICONST=IXNY(JPHI)+IZERO(JPHI)                                     CAS21370
      IEWPHI=IEW(JPHI)                                                  CAS21380
      NODE2=NODEL                                                       CAS21390
      IF(JPHI.EQ.JV) NODE2=NODEL1                                       CAS21400
      NF2=NODEF+NODE2                                                   CAS21410
      A(NODEF1)=0.0                                                     CAS21420
      C(NODEF1)=PHIOLD(NODEF1)                                          CAS21430
C---------------------- FOR Y-DIRECTION TDMA TRAVERSES                  CAS21440
      IF(JPHI.NE.JPP) GO TO 12                                          CAS21450
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C----------------------- FOR P' EQUATION ONLY                           CAS21460
      DO 11 IY=NODEF,NODE2                                              CAS21470
      IYM1=IY-1                                                         CAS21480
      D(IY)=AE(IY)+AW(IY)+AN(IY)+AS(IY)-SP(IY)+TINY                     CAS21490
      C(IY)=SU(IY)                                                      CAS21500
      TERM=1./(D(IY)-B(IY)*A(IYM1))                                     CAS21510
      A(IY)=A(IY)*TERM                                                  CAS21520
11    C(IY)=(C(IY)+C(IYM1)*B(IY))*TERM                                  CAS21530
C----------------------- BACK SUBSTITUTION FOR P'                       CAS21540
      DO 111 IY=NODEF,NODE2                                             CAS21550
      IYBACK=NF2-IY                                                     CAS21560
      PHIOLD(IYBACK)=A(IYBACK)*PHIOLD(IYBACK+1)+C(IYBACK)               CAS21570
111   PP(IYBACK)=PHIOLD(IYBACK)                                         CAS21580
      RETURN                                                            CAS21590
12    IF(RELAX(JPHI).EQ.1.) GO TO 13                                    CAS21600
C----------------------- FOR PHI WITH RELAX. FACTOR .NE. 1              CAS21610
      DO 14 IY=NODEF,NODE2                                              CAS21620
      IYM1=IY-1                                                         CAS21630
      I=IY+ICONST                                                       CAS21640
      IE=I+IEWPHI                                                       CAS21650
      IW=I-IEWPHI                                                       CAS21660
      AP(IY)=AN(IY)+AS(IY)+AE(IY)+AW(IY)                                CAS21670
      SU(IY)=SU(IY)+AE(IY)*F(IE)+AW(IY)*F(IW)                           CAS21680
C----------------------- STORE AN IN STORE FOR RESIDUAL-SOURCE CAL.     CAS21690
      STORE(IY)=AN(IY)                                                  CAS21700
C----------------------- INCLUDE RELAXATION FACTOR IN TDMA COEFFICIENTS CAS21710
      D(IY)=(AP(IY)-SP(IY))*RRELAX+TINY                                 CAS21720
      C(IY)=SU(IY)+RELAX1*D(IY)*PHIOLD(IY)                              CAS21730
C----------------------- MODIFY TDMA COEFFICIENTS FOR BACK SUBSTITUTION CAS21740
      TERM=1./(D(IY)-B(IY)*A(IYM1))                                     CAS21750
      A(IY)=A(IY)*TERM                                                  CAS21760
14    C(IY)=(C(IY)+C(IYM1)*B(IY))*TERM                                  CAS21770
      GO TO 110                                                         CAS21780
C----------------------- FOR PHI --- NO RELAXATION                       CAS21790
13    DO 18 IY=NODEF,NODE2                                              CAS21800
      IYM1=IY-1                                                         CAS21810
      I=IY+ICONST                                                       CAS21820
      IE=I+IEWPHI                                                       CAS21830
      IW=I-IEWPHI                                                       CAS21840
      AP(IY)=AN(IY)+AS(IY)+AE(IY)+AW(IY)                                CAS21850
      SU(IY)=SU(IY)+AE(IY)*F(IE)+AW(IY)*F(IW)                           CAS21860
C----------------------- STORE AN IN STORE FOR RESIDUAL-SOURCE CAL.     CAS21870
      STORE(IY)=AN(IY)                                                  CAS21880
      D(IY)=AP(IY)-SP(IY)+TINY                                          CAS21890
      C(IY)=SU(IY)                                                      CAS21900
C----------------------- MODIFY TDMA COEFFS. FOR BACK SUBSTITUTION      CAS21910
      TERM=1./(D(IY)-B(IY)*A(IYM1))                                     CAS21920
      A(IY)=A(IY)*TERM                                                  CAS21930
18    C(IY)=(C(IY)+C(IYM1)*B(IY))*TERM                                  CAS21940
110   IF(KRSPHI.EQ.0) GO TO 120                                         CAS21950
C----------------------- RESIDUAL-SOURCE CALCULATIONS                   CAS21960
      DO 115 IY=NODEF,NODE2                                             CAS21970
      IF(SP(IY).LE.-1.E20) GO TO 115                                    CAS21980
      RS=(AP(IY)-SP(IY))*PHIOLD(IY)-SU(IY)                              CAS21990
     1   -STORE(IY)*PHIOLD(IY+1)-AS(IY)*PHIOLD(IY-1)                    CAS22000
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115   RSLINE(IX,JPHI)=RSLINE(IX,JPHI)+RS                                CAS22010
C----------------------- BACK SUBSTITUTION IN TDMA OPERATIONS           CAS22020
120   DO 100 IY=NODEF,NODE2                                             CAS22030
      IYBACK=NF2-IY                                                     CAS22040
      PHIOLD(IYBACK)=A(IYBACK)*PHIOLD(IYBACK+1)+C(IYBACK)               CAS22050
      I=IYBACK+ICONST                                                   CAS22060
100   F(I)=PHIOLD(IYBACK)                                               CAS22070
C----------------------- MODIFY DU AND DV FOR NON-UNITY D(IY)           CAS22080
      IF(JPHI.NE.JU) GO TO 102                                          CAS22090
      DO 103 IY=NODEF,NODE2                                             CAS22100
103   DU(IY)=DU(IY)/D(IY)                                               CAS22110
      RETURN                                                            CAS22120
102   IF(JPHI.NE.JV) RETURN                                             CAS22130
      DO 106 IY=NODEF,NODE2                                             CAS22140
106   DV(IY)=DV(IY)/D(IY)                                               CAS22150
      RETURN                                                            CAS22160
      END                                                               CAS22170
      SUBROUTINE PRINT(LPHI)                                            CAS22180
      COMMON                                                            CAS22190
     1/CASE1/UINLET,FLOWIN,RPIPE,XPIPE,FXSTEP,HINLET,HWALL              CAS22200
     2/DNY/ DYG(22),DYV(22),FV(22),FVNODE(22),R(22),RDYG(22),RDYV(22)   CAS22210
     2,RSYG(22),RSYV(22),RV(22),RVCB(22),SYG(22),SYV(22),Y(22),YV(22)   CAS22220
     3/DNYONX/AE(22),AN(22),AP(22),AS(22),AW(22),C(22),D(22),DIFE(22)   CAS22230
     3,DIFN(22),DUW(22), DIFW(22),DU(22),DV(22),EMUE(22),EMUN(22)       CAS22240
     3         ,EMUW(22),HCONE(22),HCONN(22),          HCONW(22)        CAS22250
     3,PHIOLD(22),RHOE(22),RHON(22),        RHOW(22),SP(22),SU(22)      CAS22260
     3,VOLUME(22),CONN(22),CONS(22),CONE(22),CONW(22),ESMPHI(22)        CAS22270
     4/DNX/ DXG(22),DXU(22),FU(22),FUNODE(22),KOUNT(22),RDXG(22)        CAS22280
     4,RDXU(22),RSXG(22),RSXU(22),STORE(22),SXG(22),SXU(22),X(22),XU(22)CAS22290
     5/DJPHI/ IEW(10),ILAST(10),IMON(10),IXNY(10),IZERO(10)             CAS22300
     5,JGROUP(10),KADSOR(10),KSOLVE(10),KRS(10),RELAX(10),RSREF(10)     CAS22310
     5,RSSUM(10),ITITLE(10)                                             CAS22320
      COMMON                                                            CAS22330
     6/DO/CCHECK,DP,FLOWPC,FLOWST,FLOWUP,GREAT,ILINE,IPLRS,IPREF,IPRINT CAS22340
     6,ISTEP ,IX,IX1NY,IX1NY1,IX2NY2,IXMON,IXP1,IXPREF,IYMON,IYPREF     CAS22350
     6,JEMU,JH,JLAST,JLIM1,JLIM2,JLIM3,JLIM4,JP,JPP,JRHO                CAS22360
     6,JU,JV,JVP1,KINPRI,KMPA,KRAD,KRHOMU,KTEST,LABPHI                  CAS22370
     6,LASTEP,LINEF,LINEL,NEQ,NEQP1                                     CAS22380
     6,NODEF,NODEF1,NODEL,NODEL1,NODLP1,NTDMA,NUMCOL                    CAS22390
     6,NX,NXMAX,NXM1,NXM2,NXYG,NXYP,NXYU,NXYV                           CAS22400
     6,NY,NYMAX,NYM1,NYM2,PI,RSCHEK,RSMAX,TINY                          CAS22410
      COMMON/PROP/EMUREF,PRL(10),PRT(10),RHOREF                         CAS22420
      COMMON/D2D1/APSL(22,10),RSLINE(22,10)                             CAS22430
      COMMON/D2D2/U(462),V(462),TKE(484),TED(484),H(484),PP(22),P(400)  CAS22440
     7,RHO(484),EMU(484)                                                CAS22450
     7,INLY(10),IOUT(10),KIN,KOUT,RELTKE,RELTED,ISTCH                   CAS22460
      COMMON                                                            CAS22470
     9/TURB/C1,C2,CD,SQRTCD,CD25,ECONST,CTAUTW,CYPTW,TAUTW1(22)         CAS22480
     9,TAUTW2(22),YPUST1(22),YPUST2(22)                                 CAS22490
     9,TAULW(22),XPUSLW(22),CTAULW,CXPLW                                CAS22500
     9,GENK(22),FACTKE,FACTED,JTKE,JTED,CAPPA                           CAS22510
     9,INLY1,INLY2,IOUT1,IOUT2,I1M1,I2P1,I3M1,I4P1                      CAS22520
      COMMON/ABC/AREAE                                                  CAS22530
      DIMENSION F(3766)                                                 CAS22540
      DIMENSION DIFS(22),EMUS(22),HCONS(22),RHOS(22)                    CAS22550
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      EQUIVALENCE (DIFS(2),DIFN(1)), (EMUS(2),EMUN(1))
      EQUIVALENCE (RHOS(2),RHON(1)), (AREAE,AREAW)
      EQUIVALENCE (HCONS(2),HCONN(1))
      EQUIVALENCE (F(1),U(1))
      DIMENSION A(22),B(22)
      EQUIVALENCE(A(1),AN(1)),(B(1),AS(1))
CHAPTER 1   1   1   1    PRELIMINARIES    1   1   1   1   1   1   1   1
      JPHI=LPHI
      IF(JPHI.EQ.JP) GO TO 12
C----------------------------------- FOR ALL PHI'S EXCEPT P
      KOLUM1=1
      KOLUM2=NUMCOL
10    LIMIT1=KOLUM1
      LIMIT2=KOLUM2
      LTOP=IEW(JPHI)
      LBOT=1
      IF(JPHI.NE.JU) GO TO 11
C--------------------------------------------- FOR U
      IF(LIMIT1.GT.NXM1) LIMIT1=NXM1
      IF(LIMIT2.GT.NXM1) LIMIT2=NXM1
      GO TO 20
C--------------------------------------------- FOR OTHER PHI'S
11    IF(LIMIT1.GT.NX) LIMIT1=NX
      IF(LIMIT2.GT.NX) LIMIT2=NX
      GO TO 20
C--------------------------------------------- FOR P
12    KOLUM1=2
      KOLUM2=NUMCOL+1
13    LIMIT1=KOLUM1
      LIMIT2=KOLUM2
      IF(LIMIT1.GT.NXM1) LIMIT1=NXM1
      IF(LIMIT2.GT.NXM1) LIMIT2=NXM1
      LTOP=NYM1
      LBOT=2
CHAPTER 2   2   2   2    PRINT TITLE OF VARIABLES    2   2   2   2   2
20    CONTINUE
      WRITE(6,9999)
      WRITE(6,200) ITITLE(JPHI),ITITLE(JPHI)
200   FORMAT(/1X,15HFIELD VALUES OF,1X, I4,2X,22(1H-),I4,22(1H-))
CHAPTER 3   3   3   3    PRINT FIELD VALUES    3   3   3   3   3   3
      DO 39 IIY=LBOT,LTOP
      IY=LTOP-IIY+LBOT
      DO 30 IX=LIMIT1,LIMIT2
      IF(JPHI-JU) 301,31,301
301   IF(JPHI-JV) 302,32,302
302   IF(JPHI-JP) 303,33,303
303   CONTINUE
31    I=IY+(IX-1)*NY
      GO TO 3000
32    I=IY+(IX-1)*NYM1
      GO TO 3000
33    I=IY-1+(IX-2)*NYM2
3000  I=I+IZERO(JPHI)
30    STORE(IX)=F(I)
      IF(JPHI-JV) 310,311,310
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310   WRITE(6,3100) IY,Y(IY),(STORE(IX),IX=LIMIT1,LIMIT2)               CAS23110
      GO TO 39                                                          CAS23120
311   WRITE(6,3101) IY,YV(IY),(STORE(IX),IX=LIMIT1,LIMIT2)              CAS23130
39    CONTINUE                                                          CAS23140
      IF(JPHI-JU) 320,321,320                                           CAS23150
320   WRITE(6,3102) (IX,X(IX),IX=LIMIT1,LIMIT2)                         CAS23160
      GO TO 360                                                         CAS23170
321   WRITE(6,3103) (IX,XU(IX),IX=LIMIT1,LIMIT2)                        CAS23180
360   IF(JPHI.EQ.JU) GO TO 350                                          CAS23190
      IF(JPHI.EQ.JP) GO TO 350                                          CAS23200
C--------------------------------- FOR ALL PHI'S OTHER THAN U AND P     CAS23210
      IF(LIMIT2.EQ.NX) RETURN                                           CAS23220
      KOLUM1=KOLUM1+NUMCOL                                              CAS23230
      KOLUM2=KOLUM2+NUMCOL                                              CAS23240
      GO TO 10                                                          CAS23250
C--------------------------------- FOR U AND P                          CAS23260
350   IF(LIMIT2.EQ.NXM1) RETURN                                         CAS23270
      KOLUM1=KOLUM1+NUMCOL                                              CAS23280
      KOLUM2=KOLUM2+NUMCOL                                              CAS23290
      IF(JPHI.EQ.JU) GO TO 10                                           CAS23300
      GO TO 13                                                          CAS23310
3100  FORMAT(1X,1X,2HY(,I2,2H)=,1PE9.3,2X,10(1PE9.2,1X))                CAS23320
3101  FORMAT(1X,3HYV(,I2,2H)=,1PE9.3,2X,10(1PE9.2,1X))                  CAS23330
3102  FORMAT(/5X,5HX(IX), 9X,10(I2,1H=,F6.2,1X)//)                      CAS23340
3103  FORMAT(/5X,5HXU(IX), 8X,10(I2,1H=,F5.2,1X)//)                     CAS23350
9999  FORMAT(/1X,56H( 1 = U, 2 = V, 3 = H, 4 = PP, 5 = P, 6 = RHO, 7 = ECAS23360
     1MU )/)                                                            CAS23370
      RETURN                                                            CAS23380
      END                                                               CAS23390
      SUBROUTINE TEST                                                   CAS23400
      COMMON                                                            CAS23410
     1/CASE1/UINLET,FLOWIN,RPIPE,XPIPE,FXSTEP,HINLET,HWALL              CAS23420
     2/DNY/ DYG(22),DYV(22),FV(22),FVNODE(22),R(22),RDYG(22),RDYV(22)   CAS23430
     2,RSYG(22),RSYV(22),RV(22),RVCB(22),SYG(22),SYV(22),Y(22),YV(22)   CAS23440
     3/DNYONX/AE(22),AN(22),AP(22),AS(22),AW(22),C(22),D(22),DIFE(22)   CAS23450
     3,DIFN(22),DUW(22), DIFW(22),DU(22),DV(22),EMUE(22),EMUN(22)       CAS23460
     3         ,EMUW(22),HCONE(22),HCONN(22),          HCONW(22)        CAS23470
     3,PHIOLD(22),RHOE(22),RHON(22),        RHOW(22),SP(22),SU(22)      CAS23480
     3,VOLUME(22),CONN(22),CONS(22),CONE(22),CONW(22),ESMPHI(22)        CAS23490
     4/DNX/ DXG(22),DXU(22),FU(22),FUNODE(22),KOUNT(22),RDXG(22)        CAS23500
     4,RDXU(22),RSXG(22),RSXU(22),STORE(22),SXG(22),SXU(22),X(22),XU(22)CAS23510
     5/DJPHI/ IEW(10),ILAST(10),IMON(10),IXNY(10),IZERO(10)             CAS23520
     5,JGROUP(10),KADSOR(10),KSOLVE(10),KRS(10),RELAX(10),RSREF(10)     CAS23530
     5,RSSUM(10),ITITLE(10)                                             CAS23540
      COMMON                                                            CAS23550
     6/DO/CCHECK,DP,FLOWPC,FLOWST,FLOWUP,GREAT,ILINE,IPLRS,IPREF,IPRINT CAS23560
     6,ISTEP  ,IX,IX1NY,IX1NY1,IX2NY2,IXMON,IXP1,IXPREF,IYMON,IYPREF    CAS23570
     6,JEMU,JH,JLAST,JLIM1,JLIM2,JLIM3,JLIM4,JP,JPP,JRHO                CAS23580
     6,JU,JV,JVP1,KINPRI,KMPA,KRAD,KRHOMU,KTEST,LABPHI                  CAS23590
     6,LASTEP,LINEF,LINEL,NEQ,NEQP1                                     CAS23600
     6,NODEF,NODEF1,NODEL,NODEL1,NODLP1,NTDMA,NUMCOL                    CAS23610
     6,NX,NXMAX,NXM1,NXM2,NXYG,NXYP,NXYU,NXYV                           CAS23620
     6,NY,NYMAX,NYM1,NYM2,PI,RSCHEK,RSMAX,TINY                          CAS23630
      COMMON/PROP/EMUREF,PRL(10),PRT(10),RHOREF                         CAS23640
      COMMON/D2D1/ARSL(22,10),RSLINE(22,10)                             CAS23650
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      COMMON/D2D2/U(462),V(452),TKE(484),TED(484),H(484),PP(22),P(400)  CAS23660
     7,RHO(484),EMU(484)                                                CAS23670
     7,INLY(10),IOUT(10),KIN,KOUT,RELTKE,RELTED,ISTCH                   CAS23680
      COMMON                                                            CAS23690
     9/TURB/C1,C2,CD,SQRTCD,CD25,ECONST,CTAUTW,CYPTW,TAUTW1(22)         CAS23700
     9,TAUTW2(22),YPUST1(22),YPUST2(22)                                 CAS23710
     9,TAULW(22),XPUSLW(22),CTAULW,CXPLW                                CAS23720
     9,GENK(22),FACTKE,FACTED,JTKE,JTED,CAPPA                           CAS23730
     9,INLY1,INLY2,IOUT1,IOUT2,I1M1,I2P1,I3M1,I4P1                      CAS23740
      COMMON/ABC/AREAE                                                  CAS23750
      DIMENSION F(3766)                                                 CAS23760
      DIMENSION DIFS(22),EMUS(22),HCONS(22),RHOS(22)                    CAS23770
      EQUIVALENCE (DIFS(2),DIFN(1)), (EMUS(2),EMUN(1))                  CAS23780
      EQUIVALENCE (RHOS(2),RHON(1)), (AREAE,AREAW)                      CAS23790
      EQUIVALENCE (HCONS(2),HCONN(1))                                   CAS23800
      EQUIVALENCE (F(1),U(1))                                           CAS23810
      DIMENSION A(22),B(22)                                             CAS23820
      EQUIVALENCE(A(1),AN(1)),(B(1),AS(1))                              CAS23830
CHAPTER 1   1  1  1    PRINT-OUT FOR LEVEL 1 ONWARDS     1  1  1  1  1  CAS23840
C------------------------------   GEOMETRICAL QUANTITIES RELATED TO GRIDCAS23850
      ENTRY TEST 11                                                     CAS23860
      WRITE(6,200) KTEST                                                CAS23870
200   FORMAT(/1X,26HDIAGNOSING PRINT-OUT LEVEL,I4,2X,30(1H-))           CAS23880
      WRITE(6,201) (K,X(K),DXG(K),SXG(K),K=1,NX)                        CAS23890
201   FORMAT(/1X,2HIX,1X,10H         X,10H       DXG,10H       SXG/     CAS23900
     1(1X,I2,1X,1P3E10.2))                                              CAS23910
      WRITE(6,202) (K,XU(K),DXU(K),SXU(K),FU(K),FUNODE(K),K=1,NX)       CAS23920
202   FORMAT(/1X,2HIX,1X,10H        XU,10H       DXU,10H       SXU,     CAS23930
     1 10H        FU,10H    FUNODE/(1X,I2,1X,1P5E10.2))                 CAS23940
      WRITE(6,203) (K,Y(K),R(K),DYG(K),SYG(K),K=1,NY)                   CAS23950
203   FORMAT(/1X,2HIY,1X,10H         Y,10H         R,10H       DYG,     CAS23960
     1 10H       SYG/(1X,I2,1X,1P4E10.2))                               CAS23970
      WRITE(6,204) (K,YV(K),RV(K),RVCB(K),DYV(K),SYV(K),FV(K),          CAS23980
     1 FVNODE(K),K=1,NY)                                                CAS23990
204   FORMAT(/1X,2HIY,1X,10H        YV,10H        RV,10H      RVCB,     CAS24000
     1 10H       DYV,10H       SYV,10H        FV,10H    FVNODE/         CAS24010
     2(1X,I2,1X,1P7E10.2))                                              CAS24020
      RETURN                                                            CAS24030
C---------------------------------------------- VARIABLE INFORMATION    CAS24040
      ENTRY TEST12                                                      CAS24050
      WRITE(6,300)                                                      CAS24060
300   FORMAT(//1X,30HDEPENDENT VARIABLE INFORMATION,20(1H-)/)           CAS24070
      WRITE(6,9999)                                                     CAS24080
      WRITE(6,301) NEQ,(ITITLE(K),K=1,NEQ)                              CAS24090
301   FORMAT(/1X,4HNEQ=,I4,1X,5(1H-),20(I4,1H,,1X))                     CAS24100
      IF(KSOLVE(JPP).EQ.0) GO TO 38                                     CAS24110
      WRITE(6,302)                                                      CAS24120
302   FORMAT(1X,14X,44HPRESSURE CORRECTION EQUATION IS ALSO SOLVED.)    CAS24130
38    WRITE(6,303)                                                      CAS24140
303   FORMAT(/1X,4H J  ,4HJPHI,8H  JGROUP,8H  KSOLVE,8H  KADSOR,        CAS24150
     1 8H     KRS,8H   RELAX,8H   IZERO,8H   ILAST,8H     IEW)          CAS24160
      WRITE(6,304) (K,ITITLE(K),JGROUP(K),KSOLVE(K),KADSOR(K),          CAS24170
     1 KRS(K),RELAX(K),IZERO(K),ILAST(K),IEW(K),K=1,JLAST)              CAS24180
304   FORMAT(1X,I2,2X,I4,4I8,F8.2,3I8)                                  CAS24190
      WRITE(6,305) JLIM1,JLIM2,JLIM3,JLIM4                              CAS24200
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305   FORMAT(/1X,8H   JLIM1,8H   JLIM2,8H   JLIM3,8H   JLIM4/1X,4I8)    CAS24210
9999  FORMAT(/1X,56H( 1 = U, 2 = V, 3 = H, 4 = PP, 5 = P, 6 = RHO, 7 = ECAS24220
     1MU )/)                                                            CAS24230
      RETURN                                                            CAS24240
C------------------------------------ INITIAL VALUES IN FIELD           CAS24250
      ENTRY TEST 13                                                     CAS24260
      J1=1                                                              CAS24270
      IF(KINPRI.GT.0) J1=JP                                             CAS24280
      DO 521 JPHI=J1,JLAST                                              CAS24290
      IF(JPHI.EQ.JPP) GO TO 521                                         CAS24300
      CALL PRINT(JPHI)                                                  CAS24310
521   CONTINUE                                                          CAS24320
      RETURN                                                            CAS24330
CHAPTER 2   2   2   2   2   PRINT-OUTS FOR LEVEL 2 ONWARDS   2   2   2  CAS24340
C-------- STARRED VELOCITIES AND THEIR RESIDUAL SOURCES ON TDMA LINE     CAS24350
      ENTRY TEST 21                                                     CAS24360
      IF(KTEST.GT.2) GO TO 804                                          CAS24370
      IF(LABPHI.EQ.1) WRITE(6,803) IX,KOUNT(IX)                         CAS24380
      IF(LABPHI.EQ.2.AND.IX.EQ.NXM1) WRITE(6,803) IX,KOUNT(IX)          CAS24390
803   FORMAT(/1X,53(1H-),4H IX=,I2,12H, KOUNT(IX)=,I3)                  CAS24400
804   ISYMBL=1                                                          CAS24410
      IF(LABPHI.GT.JV) ISYMBL=0                                         CAS24420
      K2=IEW(LABPHI)                                                    CAS24430
      WRITE(6,9998)                                                     CAS24440
      WRITE(6,800) IX,ISYMBL,ITITLE(LABPHI),(PHIOLD(K),K=1,K2)          CAS24450
800   FORMAT(/1X,3HIX=,I2,1H,,1X,I1,11H VALUES OF ,I4,1H*,1P5E10.2,     CAS24460
     1 5(/1X,24X,1P5E10.2))                                             CAS24470
      WRITE(6,801) ITITLE(LABPHI),IX,RSLINE(IX,LABPHI)                  CAS24480
801   FORMAT(1X,38HALGEBRAIC SUM OF RESIDUAL SOURCES OF  ,I4,6HAT IX=,  CAS24490
     1 I2,4H  IS,10X,1PE10.2)                                           CAS24500
9998  FORMAT(/1X,56H( 1 = U, 2 = V, 3 = H, 4 = PP, 5 = P, 6 = RHO, 7 = ECAS24510
     1MU )/)                                                            CAS24520
      RETURN                                                            CAS24530
C---------------------- MEAN-PRESSURE-CORRECTION QUANTITIES             CAS24540
      ENTRY TEST 22                                                     CAS24550
      WRITE(6,1080) IX,FLOWUP,FLOWST,DP                                 CAS24560
1080  FORMAT(/1X,3HIX=,I2,5H.....,7HFLOWUP,,7HFLOWST,,20HMEAN-P CORRECTICAS24570
     1ON  =,1P3E10.2)                                                   CAS24580
      WRITE(6,1082) FLOWPC                                              CAS24590
1082  FORMAT(1X,36HMEAN-PRESSURE CORRECTED FLOW RATE = ,8X,1PE10.2)     CAS24600
      K1=1+IX1NY                                                        CAS24610
      K2=K1+NYM1                                                        CAS24620
      WRITE(6,1081) (U(K),K=K1,K2)                                      CAS24630
1081  FORMAT(1X,24HMEAN-PRESS. C. U(1 - NY),1P5E10.2,                   CAS24640
     1 5(/1X,24X,1P5E10.2))                                             CAS24650
      RETURN                                                            CAS24660
C---------------------- P'-CORRECTION QUANTITIES                        CAS24670
      ENTRY TEST 23                                                     CAS24680
      WRITE(6,1093) IX.RSLINE(IX,JPP)                                   CAS24690
1093  FORMAT(/1X,42HALGEBRAIC SUM OF ERROR MASS SOURCES AT IX=,I3,      CAS24700
     1 5H   IS,14X,1PE10.2)                                             CAS24710
      WRITE(6,1090) IX,(PP(K),K=1.NY)                                   CAS24720
1090  FORMAT(/1X,3HIX=,I2,2X,12HPP(1 TO NY) ,5X,1P5E10.2,               CAS24730
     1 5(/1X,24X,1P5E10.2))                                             CAS24740
      K1=1+IXNY(JU)                                                     CAS24750
```

```
      K2=K1+NYM1                                                        CAS24760
      WRITE(6,1091) IX,(U(K),K=K1,K2)                                   CAS24770
1091  FORMAT(1X,3HIX=,I2,2X,17HPP C. U(1 TO NY) ,1P5E10.2,              CAS24780
     1 5(/1X,24X,1P5E10.2))                                             CAS24790
      K1=1+IXNY(JV)                                                     CAS24800
      K2=K1+NYM2                                                        CAS24810
      WRITE(6,1092) IX,(V(K),K=K1,K2)                                   CAS24820
1092  FORMAT(1X,3HIX=,I2,2X,17HPP C. V(1 - NYM1),1P5E10.2,              CAS24830
     1 5(/1X,24X,1P5E10.2))                                             CAS24840
      RETURN                                                            CAS24850
CHAPTER 3  3  3  3  3   PRINT-OUTS FOR LEVEL 3 ONWARDS    3  3  3  3    CAS24860
C---------------------- COEFFICIENTS OF FINITE-DIFFERENCE EQUATIONS     CAS24870
      ENTRY TEST 31                                                     CAS24880
      IF(LABPHI.EQ.1) WRITE(6,2030) IX,KOUNT(IX)                        CAS24890
      IF(LABPHI.EQ.2.AND.IX.EQ.NXM1) WRITE(6,2030) IX,KOUNT(IX)         CAS24900
2030  FORMAT(/1X,53(1H-),4H IX=,I2,12H, KOUNT(IX)=,I3)                  CAS24910
      WRITE(6,9997)                                                     CAS24920
      WRITE(6,2020) ITITLE(LABPHI),IX                                   CAS24930
2020  FORMAT(//1X,16HCOEFFICIENTS OF ,I4,2X,17HEQUATION FOR IX =,I4,2X,2CAS24940
     10(1H-)//1X,2HIY,2X,10H        AN,10H        AS,10H        AE,     CAS24950
     10H        AW,10H        SU,10H        SP,10H    PHIOLD)           CAS24960
      WRITE(6,2021) (K,AN(K),AS(K),AE(K),AW(K),SU(K),SP(K),PHIOLD(K),K=1CAS24970
     1,NY)                                                              CAS24980
2021  FORMAT(1X,I2,2X,1P7E10.2)                                         CAS24990
9997  FORMAT(/1X,56H( 1 = U, 2 = V, 3 = H, 4 = PP, 5 = P, 6 = RHO, 7 = ECAS25000
     1MU )/)                                                            CAS25010
      RETURN                                                            CAS25020
        END                                                             CAS25030
```

APPENDIX B

THE COMPUTER PROGRAM FOR PARTICLE COAGULATION

FORTRAN SYMBOL

Symbols	Meaning
CPART1 (I) CPART10 (I)	The number of particles in the 1st ∿ 10th class of sizes.
OCP (J,I)	The number of particles in the I-th class of sizes at the previous time step.
FF (I)	Array used to store the variables, CPART 1 (I) ∿ CPART10 (I).
FFF (I)	Array used to store the variables, OCP (J,I). FF (I) and FFF (I) are made equivalent to the total length of the individual variable array.
COEN (I) COES (I) COEE (I) COEW (I)	Coefficient in the fenite difference equations. These values are calculated before entering time loop.
JCP1 JCP10	Index controlling the class of particle sizes.
DELT	Time interval which is used for transient finite-difference equations.
STAN1 STAN2 STAN3	Mass transferc coefficient for particle deposition to the left hand side, the right side, the right hand side and the bottom wall, respectively.
XCP (I,J)	The variable which are made equivalent to the CPART 1 ∿ CPART 10
MONTOR (I)	The number of grid point which is used for printing out the calculated result at every time step.
CPINP (I)	The initial value of particle numbe in I-th size class.
TIMEF	Final time step.
ACCOM	The accomodation factor for the particle coalescenc (now taken as 0.3)
ALPH (I,J,K)	The coagulation factor between the I-th and the J-th class particles at the grid point K.

```
      BLOCK DATA
      COMMON
     1/CASE1/UINLET,FLOWIN,RPIPE,XPIPE,FXSTEP,HINLET,HWALL
     2/DNY/ DYG(22),DYV(22),FV(22),FVNODE(22),R(22),RDYG(22),RDYV(22)
     2,RSYG(22),RSYV(22),RV(22),RVCB(22),SYG(22),SYV(22),Y(22),YV(22)
     3/DNYONX/AE(22),AN(22),AP(22),AS(22),AW(22),C(22),D(22),DIFE(22)
     3,DIFN(22),DUW(22), DIFW(22),DU(22),DV(22),EMUE(22),EMUN(22)
     3        ,EMUW(22),HCONE(22),HCONN(22),            HCONW(22)
     3,PHIOLD(22),RHOE(22),RHON(22),          RHOW(22),SP(22),SU(22)
     3,VOLUME(22),CONN(22),CONS(22),CONE(22),CONW(22),ESMPHI(22)
     4/DNX/ DXG(22),DXU(22),FU(22),FUNODE(22),KOUNT(22),RDXG(22)
     4,RDXU(22),RSXG(22),RSXU(22),STORE(22),SXG(22),SXU(22),X(22),XU(22)
     5/DUPHI/ IEW(10),ILAST(10),IMON(10),IXNY(10),IZERO(10)
     5,JGROUP(10),KADSOR(10),KSOLVE(10),KRS(10),RELAX(10),RSREF(10)
     5,RSSUM(10),ITITLE(10),KTITLE(10),KEW(10),KLAST(10),KZERO(10)
      COMMON
     6/DO/CCHECK,DP,FLOWPC,FLOWST,FLOWUP,GREAT,ILINE,IPLRS,IPREF,IPRINT
     6,ISTEP ,IX,IX1NY,IX1NY1,IX2NY2,IXMON,IXP1,IXPREF,IYMON,IYPREF
     6,JEMU,JH,JLAST,JLIM1,JLIM2,JLIM3,JLIM4,JP,JPP,JRHO
     6,JU,JV,JVP1,KINPRI,KMPA,KRAD,KRHOMU,KTEST,LABPHI
     6,LASTEP,LINEF,LINEL,NEO,NEOP1
     6,NODEF,NODEF1,NODEL,NODEL1,NODLP1,NTDMA,NUMCOL
     6,NX,NXMAX,NXM1,NXM2,NXYG,NXYP,NXYU,NXYV
     6,NY,NYMAX,NYM1,NYM2,PI,RSCHEK,RSMAX,TINY
      COMMON/PROP/EMUREF,PRL(10),PRT(10),RHOREF
      COMMON/D2D1/ARSL(22,10),RSLINE(22,10)
      COMMON/D2D2/U(462),V(462),TKE(484),TED(484),H(484),PP(22),P(400)
     7 ,RHO(484),EMU(484)
      COMMON
     9/TURB/C1,C2,CD,SQRTCD,CD25,ECONST,CTAUTW,CYPTW,TAUTW1(22)
     9,TAUTW2(22),YPUST1(22),YPUST2(22)
     9,TAULW(22),XPUSLW(22),CTAULW,CXPLW
     9,GENK(22),FACTKE,FACTED,JTKE,JTED,CAPPA
     9,CPART1(484),CPART2(484),CPART3(484),CPART4(484),CPART5(484)
     9,CPART6(484),CPART7(484),CPART8(484),CPART9(484),CPART0(484)
      COMMON/PART1/DCP(484,10),ALPH(10,10,22),RP(10),DELT,TIME,NUMBER
     1,CNREL,COEE(484),COEN(484),COES(484),COEW(484),CPINP(10),VOLG(484)
     1,STAN1(22,10),STAN2(22,10),STAN3(22,10),JCP1,JCP2,JCP3,JCP4,JCP5
     1,JCP6,JCP7,JCP8,JCP9,JCP10,KPHI,KKLAST,MONTOR(10)
      COMMON/ABC/AREAE
      DIMENSION F(3766),FF(4840),FFF(4840)
      DIMENSION DIFS(22),EMUS(22),HCONS(22),RHOS(22)
      EQUIVALENCE (HCONS(2),HCONN(1)),(FF(1),CPART1(1))
      EQUIVALENCE (DIFS(2),DIFN(1)), (EMUS(2),EMUN(1))
      EQUIVALENCE (RHOS(2),RHON(1)), (AREAE,AREAW)
      EQUIVALENCE (F(1),U(1)),(DCP(1,1),FFF(1))
      DIMENSION A(22),B(22)
      EQUIVALENCE(A(1),AN(1)),(B(1),AS(1))
CHAPTER 1 -------------- GENERAL,FLOW PARAMETERS
      DATA GREAT,TINY,PI/1.E30,  1.E-30, 3.1415926/
      DATA RPIPE,XPIPE,UINLET,HINLET,HWALL/
     1  250.,250.,72.,0.0,0.0/
      DATA KTEST/0/
      DATA RP/0.0002,0.0004,0.0006,0.0008,0.001,0.0012,0.0014,0.0016
     1   ,0.0018,0.002/
```

```
CHAPTER 2 -------------- GRID
      DATA NXMAX,NYMAX/22,22/
      DATA KRAD/1/
      DATA FXSTEP/1.0/
CHAPTER 3 -------------- VARIABLES
      DATA JU, JV,JTKE,JTED,JH,JPP,JP,JRHO,JEMU,JLAST/
     1   1,  2,    3,  4, 5,    6,   7,  8,  9,   9/
      DATA JCP1,JCP2,JCP3,JCP4,JCP5,JCP6,JCP7,JCP8,JCP9,JCP10,KKLAST/
     11,2,3,4,5,6,7,8,9,10,10/
      DATA KSOLVE /10*1/
      DATA KRS/10*1/
      DATA KADSOR/10*1/
CHAPTER 4 -------------- PROPERTY DATA
      DATA RHOREF,EMUREF/7.2,0.06/
      DATA PRL,PRT/20*1.0/
CHAPTER 5 -------------- STARTING PREPARATIONS
      DATA IXPREF,IYPREF/2,2/
      DATA KINPRI/0/
CHAPTER 6 -------------- STEP CONTROL
CHAPTER 7 -------------- BOUNDARY CONDITIONS
      DATA C1,C2,CD,CAPPA,ECONST/
     1 1.43,1.92,0.09,0.4,9.0/
      DATA  SQRTCD,CD25/  0.3,0.54722/
      DATA  FACTKE,FACTED/0.005,0.03/
CHAPTER 8 -------------- ADVANCE
      DATA NTDMA/1/
CHAPTER 9 -------------- COMPLETE
CHAPTER 10 ------------- ADJUST
      DATA KMPA/0/
CHAPTER 11 ------------- PRINT
      DATA NUMCOL/10/
CHAPTER 12 ------------- DECIDE
      END
```

```
C     MAIN PROGRAM
      COMMON
     1/CASE1/UINLET,FLOWIN,RPIPE,XPIPE,FXSTEP,HINLET,HWALL
     2/DNY/ DYG(22),DYV(22),FV(22),FVNODE(22),R(22),RDYG(22),RDYV(22)
     2,RSYG(22),RSYV(22),RV(22),RVCB(22),SYG(22),SYV(22),Y(22),YV(22)
     3/DNYONX/AE(22),AN(22),AP(22),AS(22),AW(22),C(22),D(22),DIFE(22)
     3,DIFN(22),DUW(22), DIFW(22),DU(22),DV(22),EMUE(22),EMUN(22)
     3          ,EMUW(22),HCONE(22),HCONN(22),          HCONW(22)
     3,PHIOLD(22),RHOE(22),RHON(22),          RHOW(22),SP(22),SU(22)
     3,VOLUME(22),CONN(22),CONS(22),CONE(22),CONW(22),ESMPHI(22)
     4/DNX/ DXG(22),DXU(22),FU(22),FUNODE(22),KOUNT(22),RDXG(22)
     4,RDXU(22),RSXG(22),RSXU(22),STORE(22),SXG(22),SXU(22),X(22),XU(22)
     5/DUPHI/ IEW(10),ILAST(10),IMON(10),IXNY(10),IZERO(10)
     5,JGROUP(10),KADSOR(10),KSOLVE(10),KRS(10),RELAX(10),RSREF(10)
     5,RSSUM(10),ITITLE(10),KTITLE(10),KEW(10),KLAST(10),KZERO(10)
      COMMON
     6/DO/CCHECK,DP,FLOWPC,FLOWST,FLOWUP,GREAT,ILINE,IPLRS,IPREF,IPRINT
     6,ISTEP ,IX,IX1NY,IX1NY1,IX2NY2,IXMON,IXP1,IXPREF,IYMON,IYPREF
     6,JEMU,JH,JLAST,JLIM1,JLIM2,JLIM3,JLIM4,JP,JPP,JRHO
     6,JU,JV,JVP1,KINPRI,KMPA,KRAD,KRHOMU,KTEST,LABPHI
     6,LASTEP,LINEF,LINEL,NEQ,NEQP1
     6,NODEF,NODEF1,NODEL,NODEL1,NODLP1,NTDMA,NUMCOL
     6,NX,NXMAX,NXM1,NXM2,NXYG,NXYP,NXYU,NXYV
     6,NY,NYMAX,NYM1,NYM2,PI,RSCHEK,RSMAX,TINY
      COMMON/PROP/EMUREF,PRL(10),PRT(10),RHOREF
      COMMON/D2D1/ARSL(22,10),RSLINE(22,10)
      COMMON/D2D2/U(462),V(462),TKE(484),TED(484),H(484),PP(22),P(400)
     7 ,RHO(484),EMU(484)
     7 ,INLY(10),IOUT(10),KIN,KOUT,RELTKE,RELTED,ISTCH
      COMMON
     9/TURB/C1,C2,CD,SQRTCD,CD25,ECONST,CTAUTW,CYPTW,TAUTW1(22)
     9,TAUTW2(22),YPUST1(22),YPUST2(22)
     9,TAULW(22),XPUSLW(22),CTAULW,CXPLW
     9,GENK(22),FACTKE,FACTED,JTKE,JTED,CAPPA
     9,CPART1(484),CPART2(484),CPART3(484),CPART4(484),CPART5(484)
     9,CPART6(484),CPART7(484),CPART8(484),CPART9(484),CPART0(484)
      COMMON/PART1/OCP(484,10),ALPH(10,10,22),RP(10),DELT,TIME,NUMBER
     1,CNREL,COEE(484),COEN(484),COES(484),COEW(484),CPINP(10),VOLG(484)
     1,STAN1(22,10),STAN2(22,10),STAN3(22,10),JCP1,JCP2,JCP3,JCP4,JCP5
     1,JCP6,JCP7,JCP8,JCP9,JCP10,KPHI,KKLAST,MONTOR(10)
      COMMON/ABC/AREAE
      DIMENSION F(3766),FF(4840),FFF(4840)
      DIMENSION DIFS(22),EMUS(22),HCONS(22),RHOS(22)
      EQUIVALENCE (DIFS(2),DIFN(1)), (EMUS(2),EMUN(1))
      EQUIVALENCE (RHOS(2),RHON(1)), (AREAE,AREAW)
      EQUIVALENCE (HCONS(2),HCONN(1)),(FF(1),CPART1(1))
      EQUIVALENCE (F(1),U(1)),(OCP(1,1),FFF(1))
      DIMENSION A(22),B(22)
      EQUIVALENCE(A(1),AN(1)),(B(1),AS(1))
      DIMENSION XCP(484,10)
      EQUIVALENCE (XCP(1,1),CPART1(1))
CHAPTER 1  1  1  1  1     PRELIMINARIES    1  1  1  1  1  1  1  1  1  1
CASE1..... LAMINAR, UNIFORM-PROPERTY, DEVELOPING FLOW IN A PIPE
COMMENT..............   ALL NUMERICAL DATA ARE PUT IN VIA BLOCK DATA
      READ(5,1300) KTEST
```

```
      READ(5,1300) NX,NY
      READ(5,1301) (X(I),I=1,NX)
      READ(5,1301) (Y(I),I=1,NY)
      READ(5,1301) (F(I),I=1,3766)
      READ(5,1302) (RELAX(I),I=1,10)
      READ(5,1305) NTDMA,LASTEP,NOUTP1
      READ(5,1302) CNREL,TIMEF,DELT,ACCOM
      READ(5,1301) (CPINP(I),I=1,10)
       READ(5.1305 )  (MONTOR(I),I=1,10)
 1302 FORMAT(8F10.0)
1305  FORMAT(10I5)
      ISTEP=0
      ILINE=0
      TIME=0.0
      NUMBER=0
C  -------------------- PRINT OUT HEADINGS
      CALL OUTPH
CHAPTER 2  2  2  2  2    GRID    2  2  2  2  2  2  2  2  2  2  2  2
C ------------------- QUANTITIES RELATED TO NX AND NY
      CALL CONST2
C--------------------------------------  CALCULATE GRID QUANTITIES
      CALL GEOM
      IF(KTEST.GT.0) CALL TEST 11
CHAPTER 3  3  3  3  3    VARIABLES    3  3  3  3  3  3  3  3  3  3  3
C------------------------- CONSTANTS RELATED TO VARIABLES
      CALL CONST3
      IF(KTEST.GT.0) CALL TEST 12
CHAPTER 4  4  4  4  4    PROPERTY DATA    4  4  4  4  4  4  4  4  4  4
C------------------------------- PUT REFERENCE VALUES IN FIELD
C------------------------------- CELL-WALL DENSITY AND VISCOCITY
      DO 41 IY=1,NY
      RHON(IY)=RHOREF
      RHUS(IY)=RHOREF
      RHOE(IY)=RHOREF
      RHOW(IY)=RHOREF
      EMUN(IY)=EMUREF
      EMUS(IY)=EMUREF
      EMUE(IY)=EMUREF
41    EMUW(IY)=EMUREF
CHAPTER 5  5  5  5  5    STARTING PREPARATIONS    5  5  5  5  5  5  5
C----- I INDICES FOR REFERENCE-PRESSURE POINT AND MONITORING LOCATION
C----------------------- CALCULATE FLOWIN AND REF. RES.-SOURCE VALUES
      RSREF(JCP1)=CPINP(1)
      RSREF(JCP2)=CPINP(2)
      RSREF(JCP3)=CPINP(3)
      RSREF(JCP4)=CPINP(4)
      RSREF(JCP5)=CPINP(5)
      RSREF(JCP6)=CPINP(6)
      RSREF(JCP7)=CPINP(7)
        RSREF(JCP8 )=CPINP(8)
      RSREF(JCP9)=CPINP(9)
      RSREF(JCP10)=CPINP(10)
C-------------------------------------- INITIALIZE VARIABLE STORAGES
C     CONSTANS FOR Y+
      CYPTW=CD25*DYG(NY)/EMUREF
```

```
      CTAUTW=EMUREF/DYG(NY)                                             MAI01110
C     CONSTANTS FOR X+                                                  MAI01120
      CXPLW=CD25*DXG(2)/EMUREF                                          MAI01130
      CTAULW=EMUREF/DXG(2)                                              MAI01140
C     ZERO CLEAR                                                        MAI01150
      DO 499 I=1,4840                                                   MAI01160
      FFF(I)=0.                                                         MAI01170
  499 FF(I)=0.                                                          MAI01180
      DO 50 KPHI=1,KKLAST                                               MAI01190
      I1=KZERO(KPHI)+1                                                  MAI01200
      I2=KZERO(KPHI)+(NX-1)*NY                                          MAI01210
      DO 51 I=I1,I2                                                     MAI01220
      FFF(I)=CPINP(KPHI)                                                MAI01230
   51 FF(I)=CPINP(KPHI)                                                 MAI01240
   50 CONTINUE                                                          MAI01250
C-----------------INITIALIZE TDMA-LINE STORAGE                          MAI01260
      DO 554 IX=1,NXM1                                                  MAI01270
      I1=(IX-1)*NY+1                                                    MAI01280
      I2=(IX-1)*NY+NY                                                   MAI01290
      CPART1(I1)=0.                                                     MAI01300
      CPART1(I2)=0.                                                     MAI01310
      CPART2(I1)=0.                                                     MAI01320
      CPART2(I2)=0.                                                     MAI01330
      CPART3(I1)=0.                                                     MAI01340
      CPART3(I2)=0.                                                     MAI01350
      CPART4(I1)=0.                                                     MAI01360
      CPART4(I2)=0.                                                     MAI01370
      CPART5(I1)=0.                                                     MAI01380
      CPART5(I2)=0.                                                     MAI01390
      CPART6(I1)=0.                                                     MAI01400
      CPART6(I2)=0.                                                     MAI01410
      CPART7(I1)=0.                                                     MAI01420
      CPART7(I2)=0.                                                     MAI01430
      CPART8(I1)=0.                                                     MAI01440
      CPART8(I2)=0.                                                     MAI01450
      CPART9(I1)=0.                                                     MAI01460
      CPART9(I2)=0.                                                     MAI01470
      CPART0(I1)=0.                                                     MAI01480
      CPART0(I2)=0.                                                     MAI01490
      DO 553 KPHI=1,KKLAST                                              MAI01500
      OCP(I1,KPHI)=0.                                                   MAI01510
      OCP(I2,KPHI)=0.                                                   MAI01520
  553 CONTINUE                                                          MAI01530
  554 CONTINUE                                                          MAI01540
      DO 555 IY=1,NXYP                                                  MAI01550
  555 P(IY)=0.0                                                         MAI01560
      DO 501 IY=1,NY                                                    MAI01570
      AN(IY)=0.0                                                        MAI01580
      DV(IY)=0.0                                                        MAI01590
      AS(IY)=0.0                                                        MAI01600
      AE(IY)=0.0                                                        MAI01610
      AW(IY)=0.0                                                        MAI01620
      SU(IY)=0.0                                                        MAI01630
      SP(IY)=0.0                                                        MAI01640
      DU(IY)=0.0                                                        MAI01650
```

```
      VOLUME(IY)=0.0                                                    MAI01660
      PP(IY)=0.0                                                        MAI01670
501   PHIOLD(IY)=0.0                                                    MAI01680
C_______________INITIALIZE Y-DIRECTION ARRAYS                           MAI01690
      DO 502 IX=1,NX                                                    MAI01700
      YPUST1(IX)=0.0                                                    MAI01710
      YPUST2(IX)=0.0                                                    MAI01720
      TAUTW1(IX)=0.0                                                    MAI01730
  502 TAUTW2(IX)=0.0                                                    MAI01740
C--------------INITIALIZE Y-DIRECTION ARRAYS                            MAI01750
      DO 503 IY=1,NY                                                    MAI01760
      TAULW(IY)=0.0                                                     MAI01770
  503 XPUSLW(IY)=0.0                                                    MAI01780
CHAPTER 7  7  7  7  7    BOUNDARY CONDITIONS    7  7  7  7  7  7  7  7  MAI01790
C-------CALCULATE TAU AND Y+ FOR LADLE WALL LEFT                        MAI01800
      NODEL=NY-1                                                        MAI01810
      NODEF=2                                                           MAI01820
      NODEF1=NODEF-1                                                    MAI01830
      IXP1=IX+1                                                         MAI01840
      DO 7999 IX=2,NX                                                   MAI01850
      IX1NY=(IX-1)*NY                                                   MAI01860
      IX1NY1=(IX-1)*(NY-1)                                              MAI01870
      DO 7699 KPHI=1,KKLAST                                             MAI01880
 7699 IXNY(KPHI)=(IX-1)*NY                                              MAI01890
      I=2+IX1NY                                                         MAI01900
      IE=I-NY                                                           MAI01910
      UP=U(IE)+(U(I)-U(IE))*FUNODE(IX)                                  MAI01920
      ABSUP=ABS(UP)                                                     MAI01930
      IF(IX.EQ.2.AND.ABSUP.LE.TINY) UP=TINY                             MAI01940
      RSQRTK=RHO(I)*SQRT(TKE(I))                                        MAI01950
      YPUST1(IX)=RSQRTK*CYPTW                                           MAI01960
      IF(YPUST1(IX).GT.11.5) GO TO 701                                  MAI01970
      TAUTW1(IX)=CTAUTW*UP                                              MAI01980
      GO TO 710                                                         MAI01990
  701 TAUTW1(IX)=CAPPA*UP*RSQRTK*CD25/ALOG(ECONST*YPUST1(IX))            MAI02000
  710 CONTINUE                                                          MAI02010
C---------CALCULATE TAU AND Y+ FORLADLE WALL- RIGHT                     MAI02020
      I=NYM1+IX1NY                                                      MAI02030
      IW=I-NY                                                           MAI02040
      UP=U(IW)+(U(I)-U(IW))*FUNODE(IX)                                  MAI02050
      ABSUP=ABS(UP)                                                     MAI02060
      IF(IX.EQ.2.AND.ABSUP.LE.TINY) UP=TINY                             MAI02070
       RSQRTK=RHO(I)*SQRT(TKE(I))                                       MAI02080
      YPUST2(IX)=RSQRTK*CYPTW                                           MAI02090
      IF(YPUST2(IX).GT.11.5) GO TO 702                                  MAI02100
      TAUTW2(IX)=CTAUTW*UP                                              MAI02110
      GO TO 711                                                         MAI02120
  702 TAUTW2(IX)=CAPPA*UP*RSQRTK*CD25/ALOG(ECONST*YPUST2(IX))            MAI02130
  711 CONTINUE                                                          MAI02140
C  CALCULATE TAU AND X+ FOR LADLE BOTTOM                                MAI02150
      IF(IX.NE.NXM1) GO TO 720                                          MAI02160
      DO 721 IY=2,NYM1                                                  MAI02170
      I=IY+IX1NY                                                        MAI02180
      IV=IY+IX1NY1                                                      MAI02190
      ISV=IV-1                                                          MAI02200
```

```
      VP=V(ISV)+(V(IV)-V(ISV))*FVNODE(IY)
      RSQRTK=RHO(I)*SQRT(TKE(I))
      XPUSLW(IY)=RSQRTK*CXPLW
      IF(XPUSLW(IY).GT.11.5) GO TO 722
      TAULW(IY)=CTAULW*VP
      GO TO 721
  722 TAULW(IY)=CAPPA*VP*RSQRTK*CD25/ALOG(ECONST*XPUSLW(IY))
  721 CONTINUE
720   CONTINUE
      KPHI=1
      CALL COEFF(KPHI)
      DO 53 IY=2,NYM1
      I=IY+IX1NY
      COEE(I)=AE(IY)
      COEN(I)=AN(IY)
      COES(I)=AS(IY)
      COEW(I)=AW(IY)
53    VOLG(I)=VOLUME(IY)
7999  CONTINUE
      DO 7998 IX=2,NXM1
      IX1NY=(IX-1)*NY
      IX1NY1=(IX-1)*(NY-1)
      DO 7998 KPHI=1,KKLAST
      I=IX1NY+2
      COES(I)=0.
      IW=I-NY
      UA=0.5*(U(I)+U(IW))
      FRIC=ABS(TAUTW1(IX)/(RHO(I)*UA*UA))
      SQHF=SQRT(FRIC/2.)
      SPLS=4.*RHO(I)/(18.*EMUREF**2)*0.05*UA**2*SQHF*RP(KPHI)**2
      STAN1(IX,KPHI)=(FRIC/2.)/(1.+SQHF*(1525./SPLS**2-50.6))*UA
C
C
C
      I=IX1NY+NYM1
      COEN(I)=0.
      IW=I-NY
      UA=0.5*(U(I)+U(IW))
      FRIC=ABS(TAUTW2(IX)/(RHO(I)*UA*UA))
      SQHF=SQRT(FRIC/2.)
      SPLS=4.0*RHO(I)/(18.*EMUREF**2)*0.05*UA**2*SQHF*RP(KPHI)**2
      STAN2(IX,KPHI)=(FRIC/2.)/(1.+SQHF*(1525./SPLS**2-50.6))*UA
C
C
C
      IF(IX.NE.NXM1) GO TO 7998
      DO 7997 IY=2,NYM1
      I=IY   +IX1NY
      IV=IY  +IX1NY1
      COEE(I)=0.
      ISV=IV-1
      VA=0.5*(V(I)+V(ISV))
      FRIC=ABS(TAULW(IY)/(RHO(I)*VA*VA))
      SQHF=SQRT(FRIC/2.0)
      SPLS=4.0*RHO(I)/(18.*EMUREF**2)*0.05*VA**2*SQHF*RP(KPHI)**2
```

```
      STAN3(IY,KPHI)=(FRIC/2.)/(1.+SQHF*(1525./SPLS**2-50.6))*VA         MAI02760
7997  CONTINUE                                                           MAI02770
7998  CONTINUE                                                           MAI02780
C---------------- PRINT OUT STARTING VALUES                              MAI02790
4000  CONTINUE                                                           MAI02800
      NUMBER=NUMBER+1                                                    MAI02810
      TIME=TIME+DELT                                                     MAI02820
      ISTEP=1                                                            MAI02830
      IF(KTEST.GT.0) CALL TEST 13                                        MAI02840
      IF(KINPRI.GT.0) CALL OUTPF                                         MAI02850
      GO TO 60                                                           MAI02860
   55 IF(ISTEP.GT.1) GO TO 65                                            MAI02870
CHAPTER 6  6  6  6  STEP CONTROLL                                        MAI02880
   60 CONTINUE                                                           MAI02890
      DO 69 KPHI=1,KKLAST                                                MAI02900
   69 RSSUM(KPHI)=0.0                                                    MAI02910
      IF(ISTEP.GT.1) GO TO 64                                            MAI02920
      IF(ILINE.GT.0) GO TO 65                                            MAI02930
C-----------Y-DIRECTION TDMA TRAVERSES                                   MAI02940
   62 LINEF=2                                                            MAI02950
      LINEL=NXM1                                                         MAI02960
      NODEF=2                                                            MAI02970
      NODEL=NYM1                                                         MAI02980
C---------- FOR BOTH X- AND Y-DIRECTION TRAVERSES                        MAI02990
      NODEF1=NODEF-1                                                     MAI03000
      NODEL1=NODEL-1                                                     MAI03010
      NODLP1=NODEL+1                                                     MAI03020
   64 ILINE=LINEF                                                        MAI03030
C------------QUANTITIES RELATED TO IX VALUE OF TDMA LINE                 MAI03040
   65 CONTINUE                                                           MAI03050
       IX=ILINE                                                          MAI03060
      IXP1=IX+1                                                          MAI03070
      IX1NY=(IX-1)*NY                                                    MAI03080
      IX1NY1=(IX-1)*NYM1                                                 MAI03090
      IX2NY2=(IX-2)*NYM2                                                 MAI03100
      DO 66 KPHI=1,KKLAST                                                MAI03110
   66 IXNY(KPHI)=IX1NY                                                   MAI03120
CHAPTER 8  8  8  8  8    ADVANCE    8  8  8  8  8  8  8  8  8  8  8  8   MAI03130
80    CONTINUE                                                           MAI03140
C---------------- PUT NTRAVS EQUAL TO NTDMA,OR TO OTHER VALUES TO GIVE   MAI03150
C                 MULTI-TRAVERSE ON SELECTED LINES                       MAI03160
      NTRAVS=NTDMA                                                       MAI03170
C---------------------- PUT GREAT INTO ARSL'S                            MAI03180
      DO 85 J=1,KKLAST                                                   MAI03190
85    ARSL(IX,J)=GREAT                                                   MAI03200
C - OUTER LOOP FOR CARRYING OUT A MAX. OF NTRAVS TRAVERSES ON LINE IX    MAI03210
      KOUNT(IX)=NT                                                       MAI03220
      RSMAX=0.                                                           MAI03230
C - INNER LOOP FOR ALL VARIABLES (PLUS ONE FOR PREPARATIONS FOR TRANSFERMAI03240
C   TO NEXT LINE OR TO NEXT SWEEP OF FIELD)                              MAI03250
      DO 1001 KPHI=1,KKLAST                                              MAI03260
      IF(NT.EQ.NTRAVS) GO TO 83                                          MAI03270
C---------------------- UPDATE UPHI ON TDMA LINE                         MAI03280
83    RSLINE(IX,KPHI)=0.0                                                MAI03290
      LABPHI=KPHI                                                        MAI03300
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      DO 899 IY=2,NYM1                                                  MAI03310
      DO 899 I=1,10                                                     MAI03320
      DO 899 J=1,10                                                     MAI03330
      II=IX1NY+IY                                                       MAI03340
  899 ALPH(I,J,IY)=1.67*((RP(I)+RP(J))*0.5)**3*(TED(II)/EMUREF*RHOREF)**MAI03350
     1 0.5*ACCOM                                                        MAI03360
      KCONST=IXNY(KPHI)+KZERO(KPHI)                                     MAI03370
      KEWPHI=KEW(KPHI)                                                  MAI03380
      DO 898 IY=NODEF,NODEL                                             MAI03390
      I=IY+KCONST                                                       MAI03400
  898  PHIOLD(IY)=FF(I)                                                 MAI03410
      I1=NODEF-1+KCONST                                                 MAI03420
      IL=NODEL+1+KCONST                                                 MAI03430
      PHIOLD(NODEF1)=FF(I1)                                             MAI03440
      PHIOLD(NODLP1)=FF(IL)                                             MAI03450
      CALL SOURC1(KPHI)                                                 MAI03460
      CALL MODIFY(KPHI)                                                 MAI03470
      CALL SOLVE(KPHI)                                                  MAI03480
      IF(ILINE.NE.2) GO TO 8201                                         MAI03490
      I1=IX1NY+5                                                        MAI03500
      I2=IX1NY+6                                                        MAI03510
      I3=IX1NY+14                                                       MAI03520
      I4=IX1NY+15                                                       MAI03530
      XCP(I2,KPHI)=XCP(I3,KPHI)                                         MAI03540
      XCP(I1,KPHI)=XCP(I4,KPHI)                                         MAI03550
 8201 CONTINUE                                                          MAI03560
         CALL BOUND(KPHI)                                               MAI03570
      RSLINE(IX,KPHI)=RSLINE(IX,KPHI)/RSREF(KPHI)                       MAI03580
      ABSRS=ABS(RSLINE(IX,KPHI))                                        MAI03590
      ARSL(IX,KPHI)=ABSRS                                               MAI03600
      RSMAX=AMAX1(RSMAX,ABSRS)                                          MAI03610
 1001 CONTINUE                                                          MAI03620
      IF(ILINE.EQ.LINEL) GO TO 110                                      MAI03630
      ILINE=ILINE+1                                                     MAI03640
      GO TO 65                                                          MAI03650
C---------------------- END OF INNER J-LOOP                             MAI03660
C---------------------- END OF OUTER NTRAVS LOOP                        MAI03670
CHAPTER 11  11  11  11  PRINT     11  11  11  11  11  11  11  11  11    MAI03680
  110 CONTINUE                                                          MAI03690
      ILINE=0                                                           MAI03700
C---------------------- PRINT OUT RESIDUAL SOURCES AND VARIABLE VALUES  MAI03710
C                       AT MONITORING LOCATION (IXMON,IYMON)            MAI03720
CHAPTER 12  12  12  12  DECIDE    12  12  12  12  12  12  12  12  12    MAI03730
C---------------------- CONVERGENCE CHECK                               MAI03740
C---------------------- CHECK IF LAST STEP IS REACHED                   MAI03750
      CALL OUTP1                                                        MAI03760
      IF(ISTEP.GE.LASTEP) GO TO 129                                     MAI03770
  128 ISTEP=ISTEP+1                                                     MAI03780
      GO TO 60                                                          MAI03790
  129 CONTINUE                                                          MAI03800
      IF(NUMBER.EQ.2)DELT=20.                                           MAI03810
      IF(NUMBER.EQ.4) DELT=30                                           MAI03820
      IF(NUMBER.EQ.6) DELT=60.                                          MAI03830
      IF(NUMBER.EQ.9) DELT=100.                                         MAI03840
      ISTEP=0                                                           MAI03850
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```
      IF(NUMBER.EQ.6) CALL OUTPF                                        MAI03860
      IF(NUMBER.EQ.9) CALL OUTPF                                        MAI03870
      DO 1299 I=1,4840                                                  MAI03880
 1299 FFF(I)=FF(I)                                                      MAI03890
      IF(TIME.LT.TIMEF) GO TO 4000                                      MAI03900
      CALL OUTPF                                                        MAI03910
      STOP                                                              MAI03920
 1300 FORMAT(2I4)                                                       MAI03930
 1301 FORMAT(5E13.5)                                                    MAI03940
      END                                                               MAI03950
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      SUBROUTINE SOLVE(LPHI)
      COMMON
     1/CASE1/UINLET,FLOWIN,RPIPE,XPIPE,FXSTEP,HINLET,HWALL
     2/DNY/ DYG(22),DYV(22),FV(22),FVNODE(22),R(22),RDYG(22),RDYV(22)
     2,RSYG(22),RSYV(22),RV(22),RVCB(22),SYG(22),SYV(22),Y(22),YV(22)
     3/DNYONX/AE(22),AN(22),AP(22),AS(22),AW(22),C(22),D(22),DIFE(22)
     3,DIFN(22),DUW(22), DIFW(22),DU(22),DV(22),EMUE(22),EMUN(22)
     3          ,EMUW(22),HCONE(22).HCONN(22),           HCONW(22)
     3,PHIOLD(22),RHOE(22),RHON(22),          RHOW(22),SP(22),SU(22)
     3,VOLUME(22),CONN(22),CONS(22),CONE(22),CONW(22),ESMPHI(22)
     4/DNX/ DXG(22).DXU(22),FU(22),FUNODE(22),KOUNT(22),RDXG(22)
     4,RDXU(22),RSXG(22),RSXU(22),STORE(22).SXG(22),SXU(22),X(22),XU(22)
     5/DJPHI/ IEW(10),ILAST(10),IMON(10),IXNY(10),IZERO(10)
     5,JGROUP(10),KADSOR(10),KSOLVE(10),KRS(10),RELAX(10),RSREF(10)
     5,RSSUM(10),ITITLE(10),KTITLE(10),KEW(10),KLAST(10),KZERO(10)
      COMMON
     6/DO/CCHECK,DP,FLOWPC,FLOWST,FLOWUP,GREAT,ILINE,IPLRS,IPREF,IPRINT
     6,ISTEP ,IX,IX1NY,IX1NY1,IX2NY2,IXMON,IXP1,IXPREF,IYMON,IYPREF
     6,JEMU,JH,JLAST,JLIM1,JLIM2,JLIM3,JLIM4,JP,JPP,JRHO
     6,JU,JV,JVP1,KINPRI,KMPA,KRAD,KRHOMU,KTEST,LABPHI
     6,LASTEP,LINEF,LINEL,NEQ,NEQP1
     6,NODEF,NODEF1,NODEL,NODEL1,NODLP1,NTDMA,NUMCOL
     6,NX,NXMAX,NXM1,NXM2,NXYG,NXYP,NXYU,NXYV
     6,NY,NYMAX,NYM1,NYM2,PI,RSCHEK,RSMAX,TINY
      COMMON/PROP/EMUREF,PRL(10),PRT(10),RHOREF
      COMMON/D2D1/ARSL(22,10),RSLINE(22,10)
      COMMON/D2D2/U(462),V(462),TKE(484),TED(484),H(484),PP(22),P(400)
     7,RHO(484),EMU(484)
     7,INLY(10),IOUT(10),KIN,KOUT,RELTKE,RELTED,ISTCH
      COMMON
     9/TURB/C1,C2,CD,SQRTCD,CD25,ECONST,CTAUTW,CYPTW,TAUTW1(22)
     9,TAUTW2(22),YPUST1(22),YPUST2(22)
     9,TAULW(22),XPUSLW(22),CTAULW,CXPLW
     9,GENK(22),FACTKE,FACTED,JTKE,JTED,CAPPA
     9,CPART1(484),CPART2(484),CPART3(484),CPART4(484),CPART5(484)
     9,CPART6(484),CPART7(484),CPART8(484),CPART9(484),CPART0(484)
      COMMON/PART1/OCP(484,10),ALPH(10,10,22),RP(10),DELT,TIME,NUMBER
     1,CNREL,CDFE(484),CDEN(484),CDES(484),CDEW(484),CPINP(10),VOLG(484)
     1,STAN1(22,10),STAN2(22,10),STAN3(22,10),JCP1,JCP2,JCP3,JCP4,JCP5
     1,JCP6,JCP7,JCP8,JCP9,JCP10,KPHI,KKLAST,MONTOR(10)
      COMMON/ABC/AREAE
      DIMENSION F(3766),FF(4840),FFF(4840)
      DIMENSION DIFS(22),EMUS(22),HCONS(22),RHOS(22)
      EQUIVALENCE (DIFS(2),DIFN(1)), (EMUS(2),EMUN(1))
      EQUIVALENCE (RHOS(2),RHON(1)), (AREAE,AREAW)
      EQUIVALENCE (HCONS(2),HCONN(1)),(FF(1),CPART1(1))
      EQUIVALENCE (F(1).U(1)),(DCP(1,1),FFF(1))
      DIMENSION A(22),B(22)
      EQUIVALENCE(A(1),AN(1)),(B(1).AS(1))
COMMENT...... A AND B HAVE BEEN MADE EQUIVALENT TO AN, AS RESPECTIVELY
      KPHI=LPHI
      RRELAX=1./RELAX(KPHI)
      RELAX1=1.-RELAX(KPHI)
      KRSPHI=KRS(KPHI)
      KCONST=IXNY(KPHI)+KZERO(KPHI)
```

```
      IEWPHI=KEW(KPHI)
      NODE2=NODEL
      NF2=NODEF+NODE2
      A(NODEF1)=0.0
      C(NODEF1)=PHIOLD(NODEF1)
C---------------------- FOR Y-DIRECTION TDMA TRAVERSES
12    IF(RELAX(KPHI).EQ.1.) GO TO 13
C---------------------- FOR PHI WITH RELAX. FACTOR .NE. 1
      DO 14 IY=NODEF,NODE2
      IYM1=IY-1
      I=IY+KCONST
      IE=I+IEWPHI
      IW=I-IEWPHI
      AP(IY)=AN(IY)+AS(IY)+AE(IY)+AW(IY)
      SU(IY)=SU(IY)+AE(IY)*F(IE)+AW(IY)*F(IW)
C---------------------- STORE AN IN STORE FOR RESIDUAL-SOURCE CAL.
      STORE(IY)=AN(IY)
C---------------------- INCLUDE RELAXATION FACTOR IN TDMA COEFFICIENTS
      D(IY)=(AP(IY)-SP(IY))*RRELAX+TINY
      C(IY)=SU(IY)+RELAX1*D(IY)*PHIOLD(IY)
C---------------------- MODIFY TDMA COEFFICIENTS FOR BACK SUBSTITUTION
      TERM=1./(D(IY)-B(IY)*A(IYM1))
      A(IY)=A(IY)*TERM
14    C(IY)=(C(IY)+C(IYM1)*B(IY))*TERM
      GO TO 110
C---------------------- FOR PHI --- NO RELAXATION
13    DO 18 IY=NODEF,NODE2
      IYM1=IY-1
      I=IY+KCONST
      IE=I+IEWPHI
      IW=I-IEWPHI
      IMT=IY+(IX-1)*NY
      IME=IMT+NY
      IMW=IMT-NY
      IMN=IMT+1
      IMS=IMT-1
      AE(IY)=COEE(IMT)
      AN(IY)=COEN(IMT)
      AS(IY)=COES(IMT)
      AW(IY)=COEW(IMT)
      VOLUME(IY)=VOLG(IMT)
      SP(IY)=VOLUME(IY)*SP(IY)*RHOREF
         AP(IY)=((RHO(IMT)*VOLUME(IY))/(CNREL*DELT))+AN(IY)
     1  +AS(IY)+AW(IY)+AE(IY)
      SU(IY)=AE(IY)*FF(IE)+AW(IY)*FF(IW)+SU(IY)*RHO(IMT)*VOLUME(IY)
     1     +((VOLUME(IY)*RHO(IMT))/(CNREL*DELT))*OCP(IMT,KPHI)
C---------------------- STORE AN IN STORE FOR RESIDUAL-SOURCE CAL.
      STORE(IY)=AN(IY)
      D(IY)=AP(IY)-SP(IY)+TINY
      C(IY)=SU(IY)
C---------------------- MODIFY TDMA COEFFS. FOR BACK SUBSTITUTION
      TERM=1./(D(IY)-B(IY)*A(IYM1))
      A(IY)=A(IY)*TERM
18    C(IY)=(C(IY)+C(IYM1)*B(IY))*TERM
110   IF(KRSPHI.EQ.0) GO TO 120
```

```
C---------------------- RESIDUAL-SOURCE CALCULATIONS
      DO 115 IY=NODEF,NODE2
      IF(SP(IY).LE.-1.E20) GO TO 115
      RS=(AP(IY)-SP(IY))*PHIOLD(IY)-SU(IY)
     1   -STORE(IY)*PHIOLD(IY+1)-AS(IY)*PHIOLD(IY-1)
115   RSLINE(IX,KPHI)=RSLINE(IX,KPHI)+RS
C---------------------- BACK SUBSTITUTION IN TDMA OPERATIONS
120   DO 100 IY=NODEF,NODE2
      IYBACK=NF2-IY
      PHIOLD(IYBACK)=A(IYBACK)*PHIOLD(IYBACK+1)+C(IYBACK)
      I=IYBACK+KCONST
100   FF(I)=PHIOLD(IYBACK)
      RETURN
      END
```

```
      SUBROUTINE SOURC1(LPHI)
      COMMON
     1/CASE1/UINLET,FLOWIN,RPIPE,XPIPE,FXSTEP,HINLET,HWALL
     2/DNY/ DYG(22),DYV(22),FV(22),FVNODE(22),R(22),RDYG(22),RDYV(22)
     2,RSYG(22),RSYV(22),RV(22),RVCB(22),SYG(22),SYV(22),Y(22),YV(22)
     3/DNYONX/AE(22),AN(22),AP(22),AS(22),AW(22),C(22),D(22),DIFE(22)
     3,DIFN(22),DUW(22), DIFW(22),DU(22),DV(22),EMUE(22),EMUN(22)
     3         ,EMUW(22),HCONE(22),HCONN(22),          HCONW(22)
     3,PHIOLD(22),RHOE(22),RHON(22),          RHOW(22),SP(22),SU(22)
     3,VOLUME(22),CONN(22),CONS(22),CONE(22),CONW(22),ESMPHI(22)
     4/DNX/ DXG(22),DXU(22),FU(22),FUNODE(22),KOUNT(22),RDXG(22)
     4,RDXU(22),RSXG(22),RSXU(22),STORE(22),SXG(22),SXU(22),X(22),XU(22)
     5/DJPHI/ IEW(10),ILAST(10),IMON(10),IXNY(10),IZERO(10)
     5,JGROUP(10),KADSOR(10),KSOLVE(10),KRS(10),RELAX(10),RSREF(10)
     5,RSSUM(10),ITITLE(10),KTITLE(10),KEW(10),KLAST(10),KZERO(10)
      COMMON
     6/DO/CCHECK,DP,FLOWPC,FLOWST,FLOWUP,GREAT,ILINE,IPLRS,IPREF,IPRINT
     6,ISTEP  ,IX,IX1NY,IX1NY1,IX2NY2,IXMON,IXP1,IXPREF,IYMON,IYPREF
     6,JEMU,JH,JLAST,JLIM1,JLIM2,JLIM3,JLIM4,JP,JPP,JRHO
     6,JU,JV,JVP1,KINPRI,KMPA,KRAD,KRHOMU,KTEST,LABPHI
     6,LASTEP,LINEF,LINEL,NEQ,NEQP1
     6,NODEF,NODEF1,NODEL,NODEL1,NODLP1,NTDMA,NUMCOL
     6,NX,NXMAX,NXM1,NXM2,NXYG,NXYP,NXYU,NAYV
     6,NY,NYMAX,NYM1,NYM2,PI,RSCHEK,RSMAX,TINY
      COMMON/PROP/EMUREF,PRL(10),PRT(10),RHOREF
      COMMON/D2D1/ARSL(22,10),RSLINE(22,10)
      COMMON/D2D2/U(462),V(462),TKE(484),TED(484),H(484),PP(22),P(400)
     7,RHO(484),EMU(484)
     7,INLY(10),IOUT(10),KIN,KOUT,RELTKE,RELTED,ISTCH
      COMMON
     9/TURB/C1,C2,CD,SQRTCD,CD25,ECONST,CTAUTW,CYPTW,TAUTW1(22)
     9,TAUTW2(22),YPUST1(22),YFUST2(22)
     9,TAULW(22),XPUSLW(22),CTAULW,CXPLW
     9,GENK(22),FACTKE,FACTED,JTKE,JTED,CAPPA
     9,CPART1(484),CPART2(434),CPART3(484),CPART4(484),CPART5(484)
     9,CPART6(484),CPART7(484),CPART8(484),CPART9(484),CPART0(484)
      COMMON/PART1/OCP(484,10),ALPH(10,10,22),RP(10),DELT,TIME,NUMBER
     1,CNREL,COEE(484),COEN(484),COES(484),COEW(484),CPINP(10),VOLG(484)
     1,STAN1(22,10),STAN2(22,10),STAN3(22,10),JCP1,JCP2,JCP3,JCP4,JCP5
     1,JCP6,JCP7,JCP8,JCP9,JCP10,KPHI,KKLAST,MONTOR(10)
      COMMON/ABC/AREAE
      DIMENSION F(3766),FF(4840),FFF(4840)
      DIMENSION DIFS(22),EMUS(22),HCONS(22),RHOS(22)
      EQUIVALENCE (DIFS(2),DIFN(1)), (EMUS(2),EMUN(1))
      EQUIVALENCE (RHOS(2),RHON(1)), (AREAE,AREAW)
      EQUIVALENCE (HCONS(2),HCONN(1)),(FF(1),CPART1(1))
      EQUIVALENCE (F(1),U(1)),(OCP(1,1),FFF(1))
      DIMENSION A(22),B(22)
      EQUIVALENCE(A(1),AN(1)),(B(1),AS(1))
      DIMENSION XCP(484,10)
      EQUIVALENCE(XCP(1,1),CPART1(1))
CHAPTER 1  1  1  1  1    PRELIMINARIES    1  1  1  1  1  1  1  1  1  1
      KPHI=LPHI
      DO 10 IY=1,NY
      SU(IY)=0.
```

```
   10 SP(IY)=0.
      IF(KPHI.EQ.JCP1) GO TO  100
      IF(KPHI.EQ.JCP2) GO TO 200
      IF(KPHI.EQ.JCP3 ) GO TO 300
      IF(KPHI.EQ.JCP4) GO TO 400
      IF(KPHI.EQ.JCP5) GO TO 500
      IF(KPHI.EQ.JCP6) GO TO 600
      IF(KPHI.EQ.JCP7) GO TO 700
      IF(KPHI.EQ.JCP8) GO TO 800
      IF(KPHI.EQ.JCP9) GO TO 900
      IF(KPHI.EQ.JCP10) GO TO 1000
      RETURN
C
C
100   CONTINUE
      DO 101  IY=2,NYM1
      I=IY+IX1NY
101   SU(IY)=0.0
      DO 102  IY=2,NYM1
      I=IY+IX1NY
      DO 103 J=2,10
  103 SP(IY)=-ALPH(1,J,IY)*XCP(I,1)*XCP(I,J)/XCP(I,KPHI)+SP(IY)
      SP(IY)=SP(IY)-0.1428*ALPH(1,1,IY)*XCP(I,1)**2./XCP(I,KPHI)
  102 CONTINUE
      RETURN
C
C
200   CONTINUE
      DO 201  IY=2,NYM1
      I=IY+IX1NY
201   SU(IY)=0.5*ALPH(1,1,IY)*XCP(I,1)**2*0.1428
      DO 202  IY=2,NYM1
      I=IY+IX1NY
      DO 203 J=3.10
203   SP(IY)=-ALPH(2,J,IY)*XCP(I,2)*XCP(I,J)/XCP(I,KPHI)+SP(IY)
      SP(IY)=-ALPH(2,1,IY)*XCP(I,1)*XCP(I,2)*0.0526/XCP(I,KPHI)
     1   -ALPH(2,2,IY)*XCP(I,2)**2*0.4216*0.5/XCP(I,KPHI)+SP(IY)
  202 CONTINUE
      RETURN
C
C
C
300   CONTINUE
      DO 301  IY=2,NYM1
      I=IY+IX1NY
  301 SU(IY)=0.0526*ALPH(2,1,IY)*XCP(I,1)*XCP(I,2)+0.4210*ALPH(2,2,IY)
     1  *XCP(I,2)**2*0.5
      DO 303 IY=2,NYM1
      I=IY+IX1NY
      DO 302 J=4,10
302   SP(IY)=-ALPH(3,J,IY)*XCP(I,3)*XCP(I,J)/XCP(I,KPHI)+SP(IY)
      SP(IY)=SP(IY)-0.027*ALPH(1,3,IY)*XCP(I,1)-0.2162
     1 *ALPH(2,3,IY)*XCP(I,2)-0.7296*ALPH(3,3,IY)*XCP(I,3)
  303 CONTINUE
      RETURN
```

```
C
C
C
400   CONTINUE
      DO 401  IY=2,NYM1
      I=IY+IX1NY
  401 SU(IY)=0.027*ALPH(3,1,IY)*XCP(I,3)*XCP(I,1)+0.2162*ALPH(2,3,IY)
     1  *XCP(I,3)*XCP(I,2)+0.7296*ALPH(3,3,IY)*XCP(I,3)**2.*0.5
      DO 403  IY=2,NYM1
      I=IY+IX1NY
      DO 402  J=4,10
402   SP(IY)=-ALPH(4,J,IY)*XCP(I,4)*XCP(I,J)/XCP(I,KPHI)+SP(IY)
      SP(IY)=SP(IY)-0.0163*ALPH(1,4,IY)*XCP(I,1)-0.1311*ALPH(2,4,IY)
     1  *XCP(I,2)-0.4425*ALPH(3,4,IY)*XCP(I,3)
  403 CONTINUE
      RETURN
C
C
C
500   CONTINUE
      DO 501  IY=2,NYM1
      I=IY+IX1NY
  501 SU(IY)=0.0163*ALPH(4,1,IY)*XCP(I,4)*XCP(I,1)+0.1311*ALPH(4,2,IY)*
     1  XCP(I,4)*XCP(I,2)+0.4425*ALPH(4,3,IY)*XCP(I,4)*XCP(I,3)+
     1  0.9671*ALPH(4,4,IY)*XCP(I,4)**2.*0.5
      DO 503  IY=2,NYM1
      I=IY+IX1NY
      DO 502  J=5,10
502   SP(IY)=-ALPH(5,J,IY)*XCP(I,5)*XCP(I,J)/XCP(I,KPHI)+SP(IY)
      SP(IY)=SP(IY)-0.0109*ALPH(5,1,IY)*XCP(I,1)-0.0878*ALPH(2,5,IY)
     1  *XCP(I,2)-0.2966*ALPH(3,5,IY)*XCP(I,3)-0.7031*ALPH(4,5,IY)*XCP(I
     1 ,4)
  503 CONTINUE
      RETURN
C
C
C
C
600    CONTINUE
      DO 601  IY=2,NYM1
      I=IY+IX1NY
  601 SU(IY)=0.0329*ALPH(4,4,IY)*XCP(I,4)**2.*0.5+0.0109*ALPH(1,5,IY)*
     1 XCP(I,1)*XCP(I,5)+0.0878*ALPH(5,2,IY)*XCP(I,5)*XCP(I,2)+
     1 0.2966*ALPH(5,3,IY)*XCP(I,3)*XCP(I,5)+0.7031*ALPH(5,4,IY)
     1 *XCP(I,5)*XCP(I,4)+0.7324*ALPH(5,5,IY)*XCP(I,5)**2.*0.5
      DO 603  IY=2,NYM1
      I=IY+IX1NY
      DO 602  J=6,10
  602 SP(IY)=-ALPH(6,J,IY)*XCP(I,6)*XCP(I,J)/XCP(I,KPHI)+SP(IY)
      SP(IY)=SP(IY)-0.0077*ALPH(6,1,IY)*XCP(I,1)-0.0629*ALPH(6,2,IY)*
     1  XCP(I,2)-0.2125*ALPH(6,3,IY)*XCP(I,3)-0.5038*ALPH(6,4,IY)*
     1 XCP(I,4)-0.9840*ALPH(6,5,IY)*XCP(I,5)
  603 CONTINUE
      RETURN
C
```

```
C
C
700   CONTINUE
      DO 701  IY=2,NYM1
      I=IY+IX1NY
  701 SU(IY)=0.2676*ALPH(5,5,IY)*XCP(I,5)**2.*0.5+0.0077*ALPH(1,6,IY)*
     1  XCP(I,6)*XCP(I,1)+0.0629*ALPH(2,6,IY)*XCP(I,2)*XCP(I,6)+
     1  0.2125*ALPH(3,6,IY)*XCP(I,3)*XCP(I,6)+0.5038*ALPH(5,4,IY)*
     1  XCP(I,6)*XCP(I,4)+0.9840*ALPH(6,5,IY)*XCP(I,6)*XCP(I,5)+
     1  0.4736*ALPH(6,6,IY)*XCP(I,6)**2.*0.5
      DO 703  IY=2,NYM1
      I=IY+IX1NY
      DO 702  J=6,10
702   SP(IY)=-ALPH(7,J,IY)*XCP(I,7)*XCP(I,J)/XCP(I,KPHI)+SP(IY)
      SP(IY)=SP(IY)-0.0058*ALPH(1,7,IY)*XCP(I,1)-0.0472*ALPH(2,7,IY)*
     1   XCP(I,2)-0.1596*ALPH(3,7,IY)*XCP(I,3)-0.3785*ALPH(4,7,IY)*XCP(I
     1  ,4)-0.7394*ALPH(5,7,IY)*XCP(I,5)
  703 CONTINUE
      RETURN
C
C
C
800     CONTINUE
      DO 801  IY=2,NYM1
      I=IY+IX1NY
  801 SU(IY)=0.5264*ALPH(6,6,IY)*XCP(I,6)**2.*0.5+0.0056*ALPH(7,1,IY)*
     1XCP(I,7)*XCP(I,1)+0.0472*ALPH(7,2,IY)*XCP(I,7)*XCP(I,2)+0.1596*ALP
     1H(7,3,IY)*XCP(I,7)*XCP(I,3)+0.3785*ALPH(7,4,IY)*XCP(I,7)*XCP(I,4)
     1+0.7394*ALPH(7,5,IY)*XCP(I,7)*XCP(I,5)+0.7636*ALPH(7,6,IY)*XCP(I,7
     1  )*XCP(I,6)+0.1984*ALPH(7,7,IY)*XCP(I,7)**2.*0.5
      DO 803  IY=2,NYM1
      I=IY+IX1NY
      DO 602  J=8,10
802   SP(IY)=-ALPH(8,J,IY)*XCP(I,8)*XCP(I,J)/XCP(I,KPHI)+SP(IY)
      SP(IY)=SP(IY)-0.0044*ALPH(8,1,IY)*XCP(I,1)-0.0367*ALPH(8,2,IY)
     1  *XCP(I,2)-0.1242*ALPH(8,3,IY)*XCP(I,3)-0.2947*ALPH(8,4,IY)
     1  *XCP(I,4)-0.5758*ALPH(8,5,IY)*XCP(I,5)-0.9951*ALPH(8,6,IY)*
     1  XCP(I,6)-0.5353*ALPH(8,7,IY)*XCP(I,7)
  803 CONTINUE
      RETURN
C
C
C
900   CONTINUE
      DO 901  IY=2,NYM1
      I=IY+IX1NY
  901 SU(IY)=0.2164*ALPH(7,6,IY)*XCP(I,7)*XCP(I,6)+0.8016*ALPH(7,7,IY)
     1  *XCP(I,7)*XCP(I,7)*0.5+0.0044*ALPH(8,1,IY)*XCP(I,8)*XCP(I,1)
     1  +0.0367*ALPH(8,2,IY)*XCP(I,8)*XCP(I,2)+0.1242*ALPH(8,3,IY)
     1  *XCP(I,8)*XCP(I,3)+0.2947*ALPH(8,4,IY)*XCP(I,8)*XCP(I,4)+
     1  0.5758*ALPH(8,5,IY)*XCP(I,8)*XCP(I,5)+0.9951*ALPH(8,6,IY)*
     1  XCP(I,8)*XCP(I,6)+0.5353*ALPH(8,7,IY)*XCP(I,8)*XCP(I,7)
      DO 903  IY=2,NYM1
      I=IY+IX1NY
      DO 902  J=7,10
```

```
902    SP(IY)=-ALPH(9,J,IY)*XCP(I,9)*XCP(I,J)/XCP(I,KPHI)+SP(IY)            SOU02210
       SP(IY)=SP(IY)-0.0035*ALPH(9,1,IY)*XCP(I,1)-0.0293*ALPH(9,2,IY)*      SOU02220
     1  XCP(I,2)-0.0994*ALPH(9,3,IY)*XCP(I,3)-0.2359*ALPH(9,4,IY)*          SOU02230
     1  XCP(I,4)-0.4610*ALPH(9,5,IY)*XCP(I,5)-0.7967*ALPH(9,6,IY)*          SOU02240
     1  XCP(I,6)                                                            SOU02250
  903 CONTINUE                                                              SOU02260
      RETURN                                                                SOU02270
C                                                                           SOU02280
C                                                                           SOU02290
C                                                                           SOU02300
C                                                                           SOU02310
1000  CONTINUE                                                              SOU02320
      DO 1001 IY=2,NYM1                                                     SOU02330
      I=IY+IX1NY                                                            SOU02340
 1001 SU(IY)=0.4647*ALPH(8,7,IY)*XCP(I,8)*XCP(I,7)+0.9278*ALPH(8,8,IY)      SOU02350
     1  *XCP(I,8)**2.*0.5+0.0035*ALPH(9,1,IY)*XCP(I,9)*XCP(I,1)+            SOU02360
     1  0.0293*ALPH(9,2,IY)*XCP(I,9)*XCP(I,2)+0.0994*ALPH(9,3,IY)*          SOU02370
     1  XCP(I,9)*XCP(I,3)+0.2359*ALPH(9,4,IY)*XCP(I,9)*XCP(I,4)+            SOU02380
     1  0.4610*ALPH(9,5,IY)*XCP(I,9)*XCP(I,5)+0.7967*ALPH(9,6,IY)*          SOU02390
     1  XCP(I,9)*XCP(I,6)+0.7828*ALPH(9,7,IY)*XCP(I,9)*XCP(I,7)+            SOU02400
     1  0.2722*ALPH(9,8,IY)*XCP(I,9)*XCP(I,8)                               SOU02410
      DO 1003 IY=2,NYM1                                                     SOU02420
      I=IY+IX1NY                                                            SOU02430
      DO 1002 J=6,10                                                        SOU02440
1002  SP(IY)=-ALPH(10,J,IY)*XCP(I,10)*XCP(I,J)/XCP(I,KPHI)+SP(IY)           SOU02450
      SP(IY)=SP(IY)-0.0027*ALPH(10,1,IY)*XCP(I,1)-0.0239*ALPH(10,2,IY)      SOU02460
     1  *XCP(I,2)-0.0813*ALPH(10,3,IY)*XCP(I,3)-0.1931*ALPH(10,4,IY)*       SOU02470
     1  XCP(I,4)-0.3773*ALPH(10,5,IY)*XCP(I,5)                              SOU02480
 1003 CONTINUE                                                              SOU02490
      RETURN                                                                SOU02500
      END                                                                   SOU02510
```

```
      SUBROUTINE PRINT(LPHI)                                            PRI00010
      COMMON                                                            PRI00020
     1/CASE1/UINLET,FLOWIN,RPIPE,XPIPE,FXSTEP,HINLET,HWALL              PRI00030
     2/DNY/ DYG(22),DYV(22),FV(22),FVNODE(22),R(22),RDYG(22),RDYV(22)   PRI00040
     2,RSYG(22),RSYV(22),RV(22),RVCB(22),SYG(22),SYV(22),Y(22),YV(22)   PRI00050
     3/DNYONX/AE(22),AN(22),AP(22),AS(22),AW(22),C(22),D(22),DIFE(22)   PRI00060
     3,DIFN(22),DUW(22). DIFW(22),DU(22),DV(22),EMUE(22),EMUN(22)       PRI00070
     3          ,EMUW(22),HCONE(22),HCONN(22),          HCONW(22)       PRI00080
     3.PHIOLD(22),RHOE(22),RHON(22),          RHOW(22),SP(22),SU(22)    PRI00090
     3,VOLUME(22),CONN(22),CCNS(22),CONE(22).CONW(22).ESMPHI(22)        PRI00100
     4/DNX/ DXG(22),DXU(22),FU(22),FUNODE(22),KOUNT(22),RDXG(22)        PRI00110
     4,RDXU(22),RSXG(22),RSXU(22).STORE(22).SXG(22),SXU(22),X(22),XU(22)PRI00120
     5/DUPHI/ IEW(10).ILAST(10),IMON(10),IXNY(10),IZERO(10)             PRI00130
     5,JGROUP(10),KADSOR(10),KSOLVE(10),KRS(10),RELAX(10),RSREF(10)     PRI00140
     5.RSSUM(10),ITITLE(10),KTITLE(10),KEW(10),KLAST(10),KZERO(10)      PRI00150
      COMMON                                                            PRI00160
     6/DO/CCHECK,DP.FLOWPC,FLOWST,FLOWUP,GREAT,ILINE,IPLRS,IPREF,IPRINT PRI00170
     6,ISTEP  ,IX,IX1NY,IX1NY1,IX2NY2,IXMON.IXP1,IXPREF,IYMON,IYPREF    PRI00180
     6,JEMU,JH,JLAST,JLIM1,JLIM2,JLIM3,JLIM4,JP,JPP,JRHO                PRI00190
     6,JU,JV,JVP1,KINPRI,KMPA,KRAD,KRHOMU,KTEST,LABPHI                  PRI00200
     6,LASTEP,LINEF,LINEL,NEQ,NEQP1                                     PRI00210
     6,NODEF,NODEF1,NODEL,NODEL1,NODLP1,NTDMA,NUMCOL                    PRI00220
     6,NX,NXMAX,NXM1,NXM2,NXYG,NXYP,NXYU,NXYV                           PRI00230
     6,NY,NYMAX,NYM1,NYM2,PI,RSCHEK,RSMAX,TINY                          PRI00240
      COMMON/PROP/EMUREF,PRL(10),PRT(10),RHOREF                         PRI00250
      COMMON/D2D1/ARSL(22,10),RSLINE(22,10)                             PRI00260
      COMMON/D2D2/U(462),V(462),TKE(484).TED(484),H(484),PP(22),P(400)  PRI00270
     7,RHO(484),EMU(484)                                                PRI00280
     7,INLY(10),IOUT(10),KIN,KOUT,RELTKE,RELTED,ISTCH                   PRI00290
      COMMON                                                            PRI00300
     9/TURB/C1,C2,CD,SORTCD,CD25,ECONST,CTAUTW,CYPTW,TAUTW1(22)         PRI00310
     9,TAUTW2(22),YPUST1(22),YPUST2(22)                                 PRI00320
     9,TAULW(22),XPUSLW(22),CTAULW,CXPLW                                PRI00330
     9,GENK(22),FACTKE.FACTED,JTKE.JTED,CAPPA                           PRI00340
     9,CPART1(484),CPART2(484).CPART3(484),CPART4(484),CPART5(484)      PRI00350
     9,CPART6(484),CPART7(484),CPART8(484),CPART9(484),CPART0(484)      PRI00360
      COMMON/PART1/OCP(484,10),ALPH(10,10,22),RP(10),DELT,TIME,NUMBER   PRI00370
     1,CNREL,COEE(484),COEN(484),COES(484),COEW(484),CPINP(10),VOLG(484)PRI00380
     1,STAN1(22.10),STAN2(22,10),STAN3(22,10),JCP1,JCP2,JCP3,JCP4,JCP5  PRI00390
     1,JCP6,JCP7,JCP8,JCP9,JCP10,KPHI,KKLAST,MONTOR(10)                 PRI00400
      COMMON/ABC/AREAE                                                  PRI00410
      DIMENSION F(3766),FF(4840),FFF(4840)                              PRI00420
      DIMENSION DIFS(22),EMUS(22),HCONS(22),RHOS(22)                    PRI00430
      EQUIVALENCE  (DIFS(2),DIFN(1)),  (EMUS(2),EMUN(1))                PRI00440
      EQUIVALENCE  (RHOS(2),RHON(1)),  (AREAE,AREAW)                    PRI00450
      EQUIVALENCE  (HCONS(2),HCONN(1)),(FF(1),CPART1(1))                PRI00460
      EQUIVALENCE  (F(1),U(1)),(OCP(1,1),FFF(1))                        PRI00470
      DIMENSION A(22),B(22)                                             PRI00480
      EQUIVALENCE(A(1),AN(1)),(B(1),AS(1))                              PRI00490
CHAPTER 1   1   1   1    PRELIMINARIES    1   1   1   1   1   1   1   1 PRI00500
      KPHI=LPHI                                                         PRI00510
C------------------------------------------ FOR ALL PHI'S EXCEPT P      PRI00520
      KOLUM1=1                                                          PRI00530
      KOLUM2=NUMCOL                                                     PRI00540
10    LIMIT1=KOLUM1                                                     PRI00550
```

```
      LIMIT2=KOLUM2
      LTOP=KEW(KPHI)
      LBOT=1
C----------------------------------------------- FOR OTHER PHI'S
11    IF(LIMIT1.GT.NX) LIMIT1=NX
      IF(LIMIT2.GT.NX) LIMIT2=NX
      GO TO 20
C----------------------------------------------- FOR P
CHAPTER 2   2   2   2    PRINT TITLE OF VARIABLES    2   2   2   2   2
20    CONTINUE
      WRITE(6,9999)
      WRITE(6,200) KTITLE(KPHI),KTITLE(KPHI)
200   FORMAT(/1X,15HFIELD VALUES OF,1X, I4,2X,22(1H-),I4,22(1H-))
CHAPTER 3   3   3   3    PRINT FIELD VALUES    3   3   3   3   3   3
      DO 39 IIY=LBOT,LTOP
      IY=LTOP-IIY+LBOT
      DO 30 IX=LIMIT1,LIMIT2
31    I=IY+(IX-1)*NY
3000  I=I+KZERO(KPHI)
30    STORE(IX)=FF(I)
310   WRITE(6,3100) IY,Y(IY),(STORE(IX),IX=LIMIT1,LIMIT2)
39    CONTINUE
320   WRITE(6,3102) (IX,X(IX),IX=LIMIT1,LIMIT2)
C------------------------------- FOR ALL PHI'S OTHER THAN U AND P
      IF(LIMIT2.EQ.NX) RETURN
      KOLUM1=KOLUM1+NUMCOL
      KOLUM2=KOLUM2+NUMCOL
      GO TO 10
C------------------------------- FOR U AND P
3100  FORMAT(1X,1X,2HY(,I2,2H)=,1PE9.3,2X,10(1PE9.2,1X))
3101  FORMAT(1X,3HYV(,I2,2H)=,1PE9.3,2X,10(1PE9.2,1X))
3102  FORMAT(/5X,5HX(IX), 9X,10(I2,1H=,F6.2,1X)//)
3103  FORMAT(/5X,6HXU(IX), 8X,10(I2,1H=,F6.2,1X)//)
9999  FORMAT(/1X,56H( 1 = U, 2 = V, 3 = H, 4 = PP, 5 = P, 6 = RHO, 7 = E
     1MU )/)
      RETURN
      END
```

```
      SUBROUTINE OUTPUT
      COMMON
     1/CASE1/UINLET,FLOWIN,RPIPE,XPIPE,FXSTEP,HINLET,HWALL
     2/DNY/ DYG(22),DYV(22),FV(22),FVNODE(22),R(22),RDYG(22),RDYV(22)
     2,RSYG(22),RSYV(22),RV(22),RVCB(22),SYG(22),SYV(22),Y(22),YV(22)
     3/DNYONX/AE(22),AN(22),AP(22),AS(22),AW(22),C(22),D(22),DIFE(22)
     3,DIFN(22),DUW(22), DIFW(22),DU(22),DV(22),EMUE(22),EMUN(22)
     3          ,EMUW(22),HCONE(22),HCONN(22),         HCONW(22)
     3,PHIOLD(22),RHOE(22),RHON(22),         RHOW(22),SP(22),SU(22)
     3,VOLUME(22),CONN(22),CONS(22),CONE(22),CONW(22),ESMPHI(22)
     4/DNX/ DXG(22),DXU(22),FU(22),FUNODE(22),KOUNT(22),RDXG(22)
     4,RDXU(22),RSXG(22),RSXU(22),STORE(22),SXG(22),SXU(22),X(22),XU(22)
     5/DJPHI/ IEW(10),ILAST(10),IMON(10),IXNY(10),IZERO(10)
     5,JGROUP(10),KADSOR(10),KSOLVE(10),KRS(10),RELAX(10),RSREF(10)
     5,RSSUM(10),ITITLE(10),KTITLE(10),KEW(10),KLAST(10),KZERO(10)
      COMMON
     6/DO/CCHECK,DP,FLOWPC,FLOWST,FLOWUP,GREAT,ILINE,IPLRS,IPREF,IPRINT
     6,ISTEP ,IX,IX1NY,IX1NY1,IX2NY2,IXMON,IXP1,IXPREF,IYMON,IYPREF
     6,JEMU,JH,JLAST,JLIM1,JLIM2,JLIM3,JLIM4,JP,JPP,JRHO
     6,JU,JV,JVP1,KINPRI,KMPA,KRAD,KRHOMU,KTEST,LABPHI
     6,LASTEP,LINEF,LINEL,NEQ,NEQP1
     6,NODEF,NODEF1,NODEL,NODEL1,NODLP1,NTDMA,NUMCOL
     6,NX,NXMAX,NXM1,NXM2,NXYG,NXYP,NXYU,NXYV
     6,NY,NYMAX,NYM1,NYM2,PI,RSCHEK,RSMAX,TINY
      COMMON/PROP/EMUREF,PRL(10),PRT(10),RHOREF
      COMMON/D2D1/ARSL(22,10),RSLINE(22.10)
      COMMON/D2D2/U(462),V(462),TKE(484),TED(484),H(484),PP(22),P(400)
     7, RHO(484),EMU(484)
     7, INLY(10),IOUT(10),KIN,KOUT,RELTKE,RELTED,ISTCH
      COMMON
     9/TURB/C1,C2,CD,SQRTCD,CD25,ECONST,CTAUTW,CYPTW,TAUTW1(22)
     9,TAUTW2(22),YPUST1(22),YPUST2(22)
     9,TAULW(22),XPUSLW(22),CTAULW,CXPLW
     9,GENK(22),FACTKE,FACTED,JTKE,JTED,CAPPA
     9,CPART1(484),CPART2(484),CPART3(484),CPART4(484),CPART5(484)
     9,CPART6(484),CPART7(484),CPART8(484),CPART9(484),CPART0(484)
      COMMON/PART1/OCP(484,10),ALPH(10,10,22),RP(10),DELT,TIME,NUMBER
     1,CNREL,COEE(484),COEN(484),COES(484),COEW(484),CPINP(10),VOLG(484)
     1,STAN1(22,10),STAN2(22,10),STAN3(22,10),JCP1,JCP2,JCP3,JCP4,JCP5
     1,JCP6,JCP7,JCP8,JCP9,JCP10,KPHI,KKLAST,MONTOR(10)
      COMMON/ABC/AREAE
      DIMENSION F(3766),FF(4840),FFF(4840)
      DIMENSION DIFS(22),EMUS(22),HCONS(22),RHOS(22)
      EQUIVALENCE (DIFS(2),DIFN(1)), (EMUS(2),EMUN(1))
      EQUIVALENCE (RHOS(2),RHON(1)), (AREAE,AREAW)
      EQUIVALENCE (HCONS(2),HCONN(1)),(FF(1),CPART1(1))
      EQUIVALENCE (F(1),U(1)),(OCP(1,1),FFF(1))
      DIMENSION A(22),B(22)
      EQUIVALENCE(A(1),AN(1)),(B(1),AS(1))
      DATA KTRIP/0/
CHAPTER 1  1  1  1  1  PRELIMINARIES  1  1  1  1  1  1  1  1  1  1  1
CHAPTER 2  2  2  2     HEADINGS    2  2  2  2  2  2  2  2  2  2  2  2
      ENTRY OUTPH
C-----------------------------         THE PROBLEM
20    WRITE(6,201)
```

```
201   FORMAT(///1X,10X,50HLAMINAR,UNIFORM-PROPERTY FLOW IN A CIRCULAR PIOUT00560
     1PE  /1X,10X,50(1H-))                                              OUT00570
C-----------------------------------     PROBLEM INFORMATION            OUT00580
      REY=RHOREF*UINLET*2.*RPIPE/EMUREF                                 OUT00590
      WRITE(6,210) XPIPE,RPIPE,UINLET,REY,HINLET,HWALL                  OUT00600
210   FORMAT(//1X,10H     XPIPE,10H     RPIPE,10H    UINLET,            OUT00610
     110H  REY. NO.,10H    HINLET,10H     HWALL/1X,1P6E10.2)            OUT00620
      WRITE(6,250) NX,NY,NXMAX,NYMAX                                    OUT00630
      WRITE(6,251) KRAD,NTDMA,KMPA,LASTEP,RSCHEK,CCHECK                 OUT00640
250   FORMAT(/1X,10H        NX,10H        NY,10H     NXMAX,10H     NYMAXOUT00650
     1/1X,4I10)                                                         OUT00660
251   FORMAT(/1X,10H      KRAD,10H     NTDMA,10H      KMPA,10H    LASTEPOUT00670
     1,10H    RSCHEK,10H    CCHECK/1X,4I10,1P2E10.2)                    OUT00680
      RETURN                                                            OUT00690
CHAPTER 3  3   3  3   3  FIELD VALUES   3  3  3  3  3  3  3  3  3  3  3 OUT00700
      ENTRY OUTPF                                                       OUT00710
      DO 31 KPHI=1,KKLAST                                               OUT00720
32    CALL PRINT(KPHI)                                                  OUT00730
31    CONTINUE                                                          OUT00740
      KTRIP=0                                                           OUT00750
      RETURN                                                            OUT00760
CHAPTER 4  4   4  4  PRINT OUT OF RESIDUAL SOURCES AND MONITORING VALUES OUT00770
      ENTRY OUTP1                                                       OUT00780
         WRITE(6.1000) TIME                                             OUT00790
      DO 50 I=1,10                                                      OUT00800
      J=MONTOR(I)                                                       OUT00810
      WRITE(6,1001) J,CPART1(J),CPART2(J),CPART3(J),CPART4(J),CPART5(J) OUT00820
50    WRITE (6,1002) CPART6(J),CPART7(J),CPART8(J),CPART9(J),CPART0(J)  OUT00830
1000  FORMAT(/1X.5HTIME=F7.2)                                           OUT00840
1001  FORMAT(I4,5E12.5)                                                 OUT00850
1002  FORMAT(4X,5E12.5)                                                 OUT00860
      RETURN                                                            OUT00870
      END                                                               OUT00880
```

```
      SUBROUTINE MODIFY(LPHI)                                           MOD00010
      COMMON                                                            MOD00020
     1/CASE1/UINLET,FLOWIN,RPIPE,XPIPE,FXSTEP,HINLET,HWALL              MOD00030
     2/DNY/ DYG(22),DYV(22),FV(22),FVNODE(22),R(22),RDYG(22),RDYV(22)   MOD00040
     2,RSYG(22),RSYV(22),RV(22),RVCB(22),SYG(22),SYV(22),Y(22),YV(22)   MOD00050
     3/DNYONX/AE(22),AN(22),AP(22),AS(22),AW(22),C(22),D(22),DIFE(22)   MOD00060
     3,DIFN(22),DUW(22), DIFW(22),DU(22),DV(22),EMUE(22),EMUN(22)       MOD00070
     3         ,EMUW(22),HCONE(22),HCONN(22),          HCONW(22)        MOD00080
     3,PHIOLD(22),RHOE(22),RHON(22),        RHOW(22),SP(22),SU(22)      MOD00090
     3,VOLUME(22),CONN(22),CONS(22),CONE(22),CONW(22),ESMPHI(22)        MOD00100
     4/DNX/ DXG(22),DXU(22),FU(22),FUNODE(22),KOUNT(22),RDXG(22)        MOD00110
     4,RDXU(22),RSXG(22),RSXU(22),STORE(22),SXG(22),SXU(22),X(22),XU(22)MOD00120
     5/DJPHI/ IEW(10),ILAST(10),IMON(10),IXNY(10),IZERO(10)             MOD00130
     5,JGROUP(10),KADSOR(10),KSOLVE(10),KRS(10),RELAX(10),RSREF(10)     MOD00140
     5,RSSUM(10),ITITLE(10),KTITLE(10),KEW(10),KLAST(10),KZERO(10)      MOD00150
      COMMON                                                            MOD00160
     6/DO/CCHECK,DP,FLOWPC,FLOWST,FLOWUP,GREAT,ILINE,IPLRS,IPREF,IPRINT MOD00170
     6,ISTEP ,IX,IX1NY,IX1NY1,IX2NY2,IXMON,IXP1,IXPREF,IYMON,IYPREF     MOD00180
     6,JEMU,JH,JLAST,JLIM1,JLIM2,JLIM3,JLIM4,JP,JPP,JRHO                MOD00190
     6,JU,JV,JVP1,KINPRI,KMPA,KRAD,KRHOMU,KTEST,LABPHI                  MOD00200
     6,LASTEP,LINEF,LINEL,NEQ,NEQP1                                     MOD00210
     6,NODEF,NODEF1,NODEL,NODEL1,NODLP1,NTDMA,NUMCOL                    MOD00220
     6,NX,NXMAX,NXM1,NXM2,NXYG,NXYP,NXYU,NXYV                           MOD00230
     6,NY,NYMAX,NYM1,NYM2,PI,RSCHEK,RSMAX,TINY                          MOD00240
      COMMON/PROP/EMUREF,PRL(10),PRT(10),RHOREF                         MOD00250
      COMMON/D2D1/ARSL(22,10),RSLINE(22,10)                             MOD00260
      COMMON/D2D2/U(462),V(462),TKE(484),TED(484),H(484),PP(22),P(400)  MOD00270
     7,RHO(484),EMU(484)                                                MOD00280
     7,INLY(10),IOUT(10),KIN,KOUT,RELTKE,RELTED,ISTCH                   MOD00290
      COMMON                                                            MOD00300
     9/TURB/C1,C2,CD,SQRTCD,CD25,ECONST,CTAUTW,CYPTW,TAUTW1(22)         MOD00310
     9,TAUTW2(22),YPUST1(22),YPUST2(22)                                 MOD00320
     9,TAULW(22),XPUSLW(22),CTAULW,CXPLW                                MOD00330
     9,GENK(22),FACTKE,FACTED,JTKE,JTED,CAPPA                           MOD00340
     9,CPART1(484),CPART2(484),CPART3(484),CPART4(484),CPART5(484)      MOD00350
     9,CPART6(484),CPART7(484),CPART8(484),CPART9(484),CPART0(484)      MOD00360
      COMMON/PART1/OCP(484,10),ALPH(10,10,22),RP(10),DELT,TIME,NUMBER   MOD00370
     1,CNREL,COEE(484),COEN(484),COES(484),COEW(484),CPINP(10),VOLG(484)MOD00380
     1,STAN1(22,10),STAN2(22,10),STAN3(22,10),JCP1,JCP2,JCP3,JCP4,JCP5  MOD00390
     1,JCP6,JCP7,JCP8,JCP9,JCP10,KPHI,KKLAST,MONTOR(10)                 MOD00400
      COMMON/ABC/AREAE                                                  MOD00410
      DIMENSION F(3766),FF(4840),FFF(4840)                              MOD00420
      DIMENSION DIFS(22),EMUS(22),HCONS(22),RHOS(22)                    MOD00430
      EQUIVALENCE (DIFS(2),DIFN(1)), (EMUS(2),EMUN(1))                  MOD00440
      EQUIVALENCE (RHOS(2),RHON(1)), (AREAE,AREAW)                      MOD00450
      EQUIVALENCE (HCONS(2),HCONN(1)),(FF(1),CPART1(1))                 MOD00460
      EQUIVALENCE (F(1),U(1)),(OCP(1,1),FFF(1))                         MOD00470
      DIMENSION A(22),B(22)                                             MOD00480
      EQUIVALENCE(A(1),AN(1)),(B(1),AS(1))                              MOD00490
CHAPTER 1  1  1  1  1    PRELIMINARIES    1  1  1  1  1  1  1  1  1  1  MOD00500
      KPHI=LPHI                                                         MOD00510
      SP(2)=SP(2)                                                       MOD00520
      SP(NYM1)=SP(NYM1)                                                 MOD00530
      IF(IX.NE.NXM1) RETURN                                             MOD00540
```

```
   10     SP(IY)=SP(IY)                                                     MOD00560
          RETURN                                                            MOD00570
          END                                                               MOD00580
```

```
      SUBROUTINE CONST                                                  CON00010
      COMMON                                                            CON00020
     1/CASE1/UINLET,FLOWIN,RPIPE,XPIPE,FXSTEP,HINLET,HWALL              CON00030
     2/DNY/ DYG(22),DYV(22),FV(22),FVNODE(22),R(22),RDYG(22),RDYV(22)   CON00040
     2,RSYG(22),RSYV(22),RV(22),RVCB(22),SYG(22),SYV(22),Y(22),YV(22)   CON00050
     3/DNYONX/AE(22),AN(22),AP(22),AS(22),AW(22),C(22),D(22),DIFE(22)   CON00060
     3,DIFN(22),DUW(22), DIFW(22),DU(22),DV(22),EMUE(22),EMUN(22)       CON00070
     3         ,EMUW(22),HCONE(22),HCONN(22),         HCONW(22)        CON00080
     3,PHIOLD(22),RHOE(22),RHON(22),        RHOW(22),SP(22),SU(22)      CON00090
     3,VOLUME(22),CONN(22),CONS(22),CONE(22),CONW(22),ESMPHI(22)        CON00100
     4/DNX/ DXG(22),DXU(22),FU(22),FUNODE(22),KOUNT(22),RDXG(22)        CON00110
     4,RDXU(22),RSXG(22),RSXU(22),STORE(22),SXG(22),SXU(22),X(22),XU(22)CON00120
     5/DJPHI/ IEW(10),ILAST(10),IMON(10),IXNY(10),IZERO(10)             CON00130
     5,JGROUP(10),KADSOR(10),KSOLVE(10),KRS(10),RELAX(10),RSREF(10)     CON00140
     5,RSSUM(10),ITITLE(10),KTITLE(10),KEW(10),KLAST(10),KZERO(10)      CON00150
      COMMON                                                            CON00160
     6/DO/CCHECK,DP,FLOWPC,FLOWST,FLOWUP,GREAT,ILINE,IPLRS,IPREF,IPRINT CON00170
     6,ISTEP ,IX,IX1NY,IX1NY1,IX2NY2,IXMON,IXP1,IXPREF,IYMON,IYPREF     CON00180
     6,JEMU,JH,JLAST,JLIM1,JLIM2,JLIM3,JLIM4,JP,JPP,JRHO                CON00190
     6,JU,JV,JVP1,KINPRI,KMPA,KRAD,KRHOMU,KTEST,LABPHI                  CON00200
     6,LASTEP,LINEF,LINEL,NEQ,NEQP1                                     CON00210
     6,NODEF,NODEF1,NODEL,NODEL1,NODLP1,NTDMA,NUMCOL                    CON00220
     6,NX,NXMAX,NXM1,NXM2,NXYG,NXYP,NXYU,NXYV                           CON00230
     6,NY,NYMAX,NYM1,NYM2,PI,RSCHEK,RSMAX,TINY                          CON00240
      COMMON/PROP/EMUREF,PRL(10),PRT(10),RHOREF                         CON00250
      COMMON/D2D1/ARSL(22,10),RSLINE(22,10)                             CON00260
      COMMON/D2D2/U(462),V(462),TKE(484),TED(484),H(484),PP(22),P(400)  CON00270
     7,RHO(484),EMU(484)                                                CON00280
     7,INLY(10),IOUT(10),KIN,KOUT,RELTKE,RELTED,ISTCH                   CON00290
      COMMON                                                            CON00300
     9/TURB/C1,C2,CD,SQRTCD,CD25,ECONST,CTAUTW,CYPTW,TAUTW1(22)         CON00310
     9,TAUTW2(22),YPUST1(22),YPUST2(22)                                 CON00320
     9,TAULW(22),XPUSLW(22),CTAULW,CXPLW                                CON00330
     9,GENK(22),FACTKE,FACTED,JTKE,JTED,CAPPA                           CON00340
     9,CPART1(484),CPART2(484),CPART3(484),CPART4(484),CPART5(484)      CON00350
     9,CPART6(484),CPART7(484),CPART8(484),CPART9(484),CPART0(484)      CON00360
      COMMON/PART1/OCP(484,10),ALPH(10,10,22),RP(10),DELT,TIME,NUMBER   CON00370
     1,CNREL,COEE(484),COEN(484),COES(484),COEW(484),CPINP(10),VOLC(484)CON00380
     1,STAN1(22,10),STAN2(22,10),STAN3(22,10),JCP1,JCP2,JCP3,JCP4,JCP5  CON00390
     1,JCP6,JCP7,JCP8,JCP9,JCP10,KPHI,KKLAST,MONTOR(10)                 CON00400
      COMMON/ABC/AREAE                                                  CON00410
      DIMENSION F(3766),FF(4840),FFF(4840)                              CON00420
      DIMENSION DIFS(22),EMUS(22),HCONS(22),RHOS(22)                    CON00430
      EQUIVALENCE (DIFS(2),DIFN(1)), (EMUS(2),EMUN(1))                  CON00440
      EQUIVALENCE (RHOS(2),RHON(1)), (AREAE,AREAW)                      CON00450
      EQUIVALENCE (HCONS(2),HCONN(1)),(FF(1),CPART1(1))                 CON00460
      EQUIVALENCE (F(1),U(1)),(OCP(1,1),FFF(1))                         CON00470
      DIMENSION A(22),B(22)                                             CON00480
      EQUIVALENCE(A(1),AN(1)),(B(1),AS(1))                              CON00490
C----------------------- CONSTANTS RELATED TO NX AND NY ----------------CON00500
      ENTRY CONST2                                                      CON00510
      NXM1=NX-1                                                         CON00520
      NXM2=NX-2                                                         CON00530
      NYM1=NY-1                                                         CON00540
      NYM2=NY-2                                                         CON00550
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C ---------------------- TOTAL NUMBER OF NODES FOR DIFFERENT VARIABLES  CON00560
      NXYG=NX*NY                                                        CON00570
      NXYP=NXM2*NYM2                                                    CON00580
      NXYU=NXM1*NY                                                      CON00590
      NXYV=NX*NYM1                                                      CON00600
      RETURN                                                            CON00610
C -------------------- CONSTANTS RELATED TO VARIABLES -----------------CON00620
      ENTRY CONST3                                                      CON00630
      KRHOMU=KSOLVE(JRHO)+KSOLVE(JEMU)                                  CON00640
C --------------------- IZERO,ILAST AND IEW FOR DIFFERENT VARIABLES    CON00650
      IZERO(1)=0                                                        CON00660
      DO 35 J=1,JLAST                                                   CON00670
      IF(J-JU) 310,301,310                                              CON00680
310   IF(J-JV) 320,302,320                                              CON00690
320   IF(J-JP) 330,303,330                                              CON00700
330   IF(J-JPP) 305,304,305                                             CON00710
301   IL=NXYU                                                           CON00720
      ILMAX=(NXMAX-1)*NYMAX                                             CON00730
      IEW(J)=NY                                                         CON00740
      GO TO 34                                                          CON00750
302   IL=NXYV                                                           CON00760
      ILMAX=NXMAX*(NYMAX-1)                                             CON00770
      IEW(J)=NYM1                                                       CON00780
      GO TO 34                                                          CON00790
303   IL=NXYP                                                           CON00800
      ILMAX=(NXMAX-2)*(NYMAX-2)                                         CON00810
      IEW(J)=NYM2                                                       CON00820
      GO TO 34                                                          CON00830
304   IL=NY                                                             CON00840
      ILMAX=NYMAX                                                       CON00850
      IEW(J)=0                                                          CON00860
      GO TO 34                                                          CON00870
305   IL=NXYG                                                           CON00880
      ILMAX=NXMAX*NYMAX                                                 CON00890
      IEW(J)=NY                                                         CON00900
34    ILAST(J)=IZERO(J)+IL                                              CON00910
      IF(J.EQ.JLAST) GO TO 35                                           CON00920
      JP1=J+1                                                           CON00930
      IZERO(JP1)=IZERO(J)+ILMAX                                         CON00940
35    CONTINUE                                                          CON00950
C ---------------------- ASSIGNING NAMES TO THE TITLE-ARRAY             CON00960
      KZERO(1)=0                                                        CON00970
      DO 45 K=1,KKLAST                                                  CON00980
      IL=NXYG                                                           CON00990
      ILMAX=NXMAX*NYMAX                                                 CON01000
      KLAST(K)=KZERO(K)+IL                                              CON01010
      KEW(K)=NY                                                         CON01020
      IF(K.EQ.KKLAST) GO TO 45                                          CON01030
      KP1=K+1                                                           CON01040
      KZERO(KP1)=KZERO(K)+ILMAX                                         CON01050
   45 CONTINUE                                                          CON01060
      ITITLE(JU)=JU                                                     CON01070
      ITITLE(JV)=JV                                                     CON01080
      ITITLE(JP)=JP                                                     CON01090
      ITITLE(JPP)=JPP                                                   CON01100
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      ITITLE(JTKE)=JTKE                                                 CON01110
      ITITLE(JTED)=JTED                                                 CON01120
      ITITLE(JRHO)=JRHO                                                 CON01130
      ITITLE(JEMU)=JEMU                                                 CON01140
      ITITLE(JH)=JH                                                     CON01150
      KTITLE(JCP1)=JCP1                                                 CON01160
      KTITLE(JCP2)=JCP2                                                 CON01170
      KTITLE(JCP3)=JCP3                                                 CON01180
      KTITLE(JCP4)=JCP4                                                 CON01190
      KTITLE(JCP5)=JCP5                                                 CON01200
      KTITLE(JCP6)=JCP6                                                 CON01210
      KTITLE(JCP7)=JCP7                                                 CON01220
      KTITLE(JCP8)=JCP8                                                 CON01230
         KTITLE(JCP9)=JCP9                                              CON01240
      KTITLE(JCP10)=JCP10                                               CON01250
      RETURN                                                            CON01260
      END                                                               CON01270
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      SUBROUTINE COEFF(LPHI)                                            COE00010
      COMMON                                                            COE00020
     1/CASE1/UINLET,FLOWIN,RPIPE,XPIPE,FXSTEP,HINLET,HWALL              COE00030
     2/DNY/ DYG(22),DYV(22),FV(22),FVNODE(22),R(22),RDYG(22),RDYV(22)   COE00040
     2,RSYG(22),RSYV(22),RV(22),RVCB(22),SYG(22),SYV(22),Y(22),YV(22)   COE00050
     3/DNYDNX/AE(22),AN(22),AP(22),AS(22),AW(22),C(22),D(22),DIFE(22)   COE00060
     3,DIFN(22),DUW(22), DIFW(22),DU(22),DV(22),EMUE(22),EMUN(22)       COE00070
     3         .EMUW(22),HCONE(22),HCONN(22),          HCONW(22)        COE00080
     3,PHIOLD(22),RHOE(22),RHON(22),        RHOW(22),SP(22),SU(22)      COE00090
     3,VOLUME(22),CONN(22),CONS(22),CONE(22),CONW(22),ESMPHI(22)        COE00100
     4/DNX/ DXG(22),DXU(22),FU(22),FUNODE(22),KOUNT(22),RDXG(22)        COE00110
     4,RDXU(22),RSXG(22),RSXU(22),STORE(22),SXG(22),SXU(22),X(22),XU(22)COE00120
     5/DJPHI/ IEW(10),ILAST(10),IMON(10),IXNY(10),IZERO(10)             COE00130
     5,JGROUP(10),KADSOR(10),KSOLVE(10),KRS(10),RELAX(10),RSREF(10)     COE00140
     5,RSSUM(10),ITITLE(10),KTITLE(10),KEW(10),KLAST(10),KZERO(10)      COE00150
      COMMON                                                            COE00160
     6/DO/CCHECK,DP,FLOWPC,FLOWST,FLOWUP,GREAT,ILINE,IPLRS,IPREF,IPRINT COE00170
     6,ISTEP ,IX,IX1NY,IX1NY1,IX2NY2,IXMON,IXP1,IXPREF,IYMON,IYPREF     COE00180
     6,JEMU,JH,JLAST,JLIM1,JLIM2,JLIM3,JLIM4,JP,JPP,JRHO                COE00190
     6,JU,JV,JVP1,KINPRI,KMPA,KRAD,KRHOMU,KTEST,LABPHI                  COE00200
     6,LASTEP,LINEF,LINEL,NEQ,NEQP1                                     COE00210
     6,NODEF,NODEF1,NODEL,NODEL1,NODLP1,NTDMA,NUMCOL                    COE00220
     6,NX,NXMAX,NXM1,NXM2,NXYG,NXYP,NXYU,NXYV                           COE00230
     6,NY,NYMAX,NYM1,NYM2,PI,RSCHEK,RSMAX,TINY                          COE00240
      COMMON/PROP/EMUREF,PRL(10),PRT(10),RHOREF                         COE00250
      COMMON/D2D1/ARSL(22,10),RSLINE(22,10)                             COE00260
      COMMON/D2D2/U(462),V(462),TKE(484),TED(484),H(484),PP(22),P(400)  COE00270
     7,RHO(484),EMU(484)                                                COE00280
     7,INLY(10),IOUT(10),KIN,KOUT,RELTKE,RELTED,ISTCH                   COE00290
      COMMON                                                            COE00300
     9/TURB/C1,C2,CD,SQRTCD,CD25,ECONST,CTAUTW,CYPTW,TAUTW1(22)         COE00310
     9,TAUTW2(22),YPUST1(22),YPUST2(22)                                 COE00320
     9,TAULW(22),XPUSLW(22),CTAULW,CXPLW                                COE00330
     9,GENK(22),FACTKE,FACTED,JTKE,JTED,CAPPA                           COE00340
     9,CPART1(484),CPART2(484),CPART3(484),CPART4(484),CPART5(484)      COE00350
     9,CPART6(484),CPART7(484),CPART8(484),CPART9(484),CPART0(484)      COE00360
      COMMON/PART1/OCP(484,10),ALPH(10,10,22),RP(10),DELT,TIME,NUMBER   COE00370
     1,CNREL,COEE(484),COEN(484),COES(484),COEW(484),CPINP(10),VOLG(484)COE00380
     1,STAN1(22,10),STAN(22,10),STAN3(22,10),JCP1,JCP2,JCP3,JCP4,JCP5   COE00390
     1,JCP6,JCP7,JCP8,JCP9,JCP10,KPHI,KKLAST,MONTOR(10)                 COE00400
      COMMON/ABC/AREAE                                                  COE00410
      DIMENSION F(3766),FF(4840),FFF(4840)                              COE00420
      DIMENSION DIFS(22),EMUS(22),HCONS(22),RHOS(22)                    COE00430
      EQUIVALENCE (DIFS(2),DIFN(1)), (EMUS(2),EMUN(1))                  COE00440
      EQUIVALENCE (RHOS(2),RHON(1)), (AREAE,AREAW)                      COE00450
      EQUIVALENCE (HCONS(2),HCONN(1)),(FF(1),CPART1(1))                 COE00460
      EQUIVALENCE (F(1),U(1)),(OCP(1,1),FFF(1))                         COE00470
      DIMENSION A(22),B(22)                                             COE00480
      EQUIVALENCE(A(1),AN(1)),(B(1),AS(1))                              COE00490
CHAPTER 1  1  1  1  1    PRELIMINARIES     1  1  1  1  1  1  1  1  1  1 COE00500
C---------------- DEFINE ARITHMETIC FUNCTION FOR COMBINING              COE00510
C                 APPROPRIATELY CONVECTION AND DIFFUSION CONTRIBUTIONS  COE00520
C-------------------------------------------------------- HYBRID SCHEME COE00530
C     CONDIF(DIFF,FCONV,CONV)=AMAX1(0., DIFF+FCONV,CONV)                COE00540
C-------------------------------------------------------- UPWIND SCHEME COE00550
```

```
      CONDIF(DIFF,FCONV,CONV)=AMAX1(DIFF,DIFF+CONV)                     COE00560
      KPHI=LPHI                                                         COE00570
      IF(KRAD.EQ.2) GO TO 12                                            COE00580
      ASSIGN 1001 TO LG                                                 COE00590
      GO TO 13                                                          COE00600
12    ASSIGN 1002 TO LG                                                 COE00610
13    CONTINUE                                                          COE00620
C---------- TRANSFER VISCOSITIES STORED IN AN( ) TO EMUN( ), ETC.       COE00630
      CALL CELPHI(KPHI,JEMU)                                            COE00640
      N2=NODEL                                                          COE00650
      EMUS(NODEF)=AS(NODEF)                                             COE00660
      DO 121 IY=NODEF,N2                                                COE00670
      EMUN(IY)=AN(IY)                                                   COE00680
      EMUE(IY)=AE(IY)                                                   COE00690
121   EMUW(IY)=AW(IY)                                                   COE00700
C---------------------- CONVECTION TERMS AND DIFFUSION-TERM*PRANDTL     COE00710
C                       NUMBER FOR GENERAL PHI EQUATIONS                COE00720
      SXGIX=SXG(IX)                                                     COE00730
      AREA=SXG(IX)*RV(NODEF1)                                           COE00740
      DIFS(NODEF)=EMUS(NODEF)*AREA*RDYG(NODEF)                          COE00750
      ISV=NODEF1+IX1NY1                                                 COE00760
      HCONS(NODEF)=0.5*RHOS(NODEF)*V(ISV)*AREA                          COE00770
      RDXGIX=RDXG(IX)                                                   COE00780
      RDXGI1=RDXG(IXP1)                                                 COE00790
      DO 156 IY=NODEF,NODEL                                             COE00800
      IYM1=IY-1                                                         COE00810
      I=IY+IX1NY                                                        COE00820
      IW=I-NY                                                           COE00830
      IV=IY+IX1NY1                                                      COE00840
      AREAN=SXGIX                                                       COE00850
      AREAE=SYG(IY)                                                     COE00860
      GO TO LG,(1001,1002)                                              COE00870
1002  AREAN=AREAN*RV(IY)                                                COE00880
      AREAE=AREAE*R(IY)                                                 COE00890
C      AREAW=AREAE   , THROUGH EQUIVALENCE                              COE00900
1001  VOLUME(IY)=AREAE*SXGIX                                            COE00910
C      DIFS(IY)=DIFN(IYM1)     , THROUGH EQUIVALENCE                    COE00920
      DIFN(IY)=EMUN(IY)*AREAN*RDYG(IY+1)                                COE00930
      DIFE(IY)=EMUE(IY)*AREAE*RDXGI1                                    COE00940
      DIFW(IY)=EMUW(IY)*AREAW*RDXGIX                                    COE00950
C      HCONS(IY)=HCONN(IYM1)   , THROUGH EQUIVALENCE                    COE00960
      HCONN(IY)=0.5*RHON(IY)*V(IV)*AREAN                                COE00970
      HCONE(IY)=0.5*RHOE(IY)*U(I)*AREAE                                 COE00980
      HCONW(IY)=0.5*RHOW(IY)*U(IW)*AREAW                                COE00990
      CONN(IY)=HCONN(IY)+HCONN(IY)                                      COE01000
      CONS(IY)=HCONS(IY)+HCONS(IY)                                      COE01010
      CONE(IY)=HCONE(IY)+HCONE(IY)                                      COE01020
      CONW(IY)=HCONW(IY)+HCONW(IY)                                      COE01030
      ESMPHI(IY)=CONS(IY)-CONN(IY)+CONW(IY)-CONE(IY)                    COE01040
156   ESMPHI(IY)=AMAX1(0.0.  -ESMPHI(IY))                               COE01050
CHAPTER 5  5  5  5  5   PHI EQUATION   5  5  5  5  5  5  5  5  5  5     COE01060
50    RPRT=1./PRT(KPHI)                                                 COE01070
C-------------------- COEFFICIENTS FOR ALL CELLS ON THE STRIP           COE01080
      KCONST=IXNY(KPHI)+KZERO(KPHI)                                     COE01090
      KEWPHI=KEW(KPHI)                                                  COE01100
```

```
      DO 56 IY=NODEF,NODEL
      I=IY+KCONST
      KE=I+IEWPHI
      IW=I-KEWPHI
      DS=DIFS(IY)*RPRT
      DN=DIFN(IY)*RPRT
      DE=DIFE(IY)*RPRT
      DW=DIFW(IY)*RPRT
C---------------------- ERROR SOURCE OF MASS
      FM=ESMPHI(IY)
C---------------- COMBINING DIFFUSION AND CONVECTION CONTRIBUTIONS
      AN(IY)=CONDIF(DN,-HCONN(IY),-CONN(IY))
      AS(IY)=CONDIF(DS, HCONS(IY), CONS(IY))
      AE(IY)=CONDIF(DE,-HCONE(IY),-CONE(IY))
      AW(IY)=CONDIF(DW, HCONW(IY), CONW(IY))
C---------------------- STORING PHI IN PHIOLD
C---------------------- SOURCE TERMS
56    CONTINUE
C---------------------- PUT BOUNDARY END VALUES IN PHIOLD
C---------------------- ADDITIONAL SOURCE TERMS IF REQUIRED
      RETURN
      END
```

```
      SUBROUTINE CELPHI(JCELL,LPHI)                                     CEL00010
      COMMON                                                            CEL00020
     1/CASE1/UINLET,FLOWIN,RPIPE,XPIPE,FXSTEP,HINLET,HWALL              CEL00030
     2/DNY/ DYG(22),DYV(22),FV(22),FVNODE(22),R(22),RDYG(22),RDYV(22)   CEL00040
     2,RSYG(22),RSYV(22),RV(22),RVCB(22),SYG(22),SYV(22),Y(22),YV(22)   CEL00050
     3/DNYONX/AE(22),AN(22),AP(22),AS(22),AW(22),C(22),D(22),DIFE(22)   CEL00060
     3,DIFN(22),DUW(22), DIFW(22),DU(22),DV(22),EMUE(22),EMUN(22)       CEL00070
     3          ,EMUW(22),HCONE(22),HCONN(22),         HCONW(22)        CEL00080
     3,PHIOLD(22),RHOE(22),RHON(22),          RHOW(22),SP(22),SU(22)    CEL00090
     3,VOLUME(22),CONN(22),CONS(22),CONE(22),CONW(22),ESMPHI(22)        CEL00100
     4/DNX/ DXG(22),DXU(22),FU(22),FUNODE(22),KOUNT(22),RDXG(22)        CEL00110
     4,RDXU(22),RSXG(22),RSXU(22),STORE(22),SXG(22),SXU(22),X(22),XU(22)CEL00120
     5/DJPHI/ IEW(10),ILAST(10),IMON(10),IXNY(10),IZERO(10)             CEL00130
     5,JGROUP(10),KADSOR(10),KSOLVE(10),KRS(10),RELAX(10),RSREF(10)     CEL00140
     5,RSSUM(10),ITITLE(10),KTITLE(10),KEW(10),KLAST(10),KZERO(10)      CEL00150
      COMMON                                                            CEL00160
     6/DO/CCHECK,DP,FLOWPC,FLOWST,FLOWUP,GREAT,ILINE,IPLRS,IPREF,IPRINT CEL00170
     6,ISTEP  ,IX,IX1NY,IX1NY1,IX2NY2,IXMON,IXP1,IXPREF,IYMON,IYPREF    CEL00180
     6,JEMU,JH,JLAST,JLIM1,JLIM2,JLIM3,JLIM4,JP,JPP,JRHO                CEL00190
     6,JU,JV,JVP1,KINPRI,KMPA,KRAD,KRHOMU,KTEST,LABPHI                  CEL00200
     6,LASTEP,LINEF,LINEL,NEQ,NEQP1                                     CEL00210
     6,NODEF,NODEF1,NODEL,NODEL1,NODLP1,NTDMA,NUMCOL                    CEL00220
     6,NX,NXMAX,NXM1,NXM2,NXYG,NXYP,NXYU,NXYV                           CEL00230
     6,NY,NYMAX,NYM1,NYM2,PI,RSCHEK,RSMAX,TINY                          CEL00240
      COMMON/PROP/EMUREF,PRL(10),PRT(10),RHOREF                         CEL00250
      COMMON/D2D1/ARSL(22,10),RSLINE(22,10)                             CEL00260
      COMMON/D2D2/U(462),V(462),TKE(484),TED(484),H(484),PP(22),P(400)  CEL00270
     7,RHO(484),EMU(484)                                                CEL00280
     7,INLY(10),IOUT(10),KIN,KOUT,RELTKE,RELTED,ISTCH                   CEL00290
      COMMON                                                            CEL00300
     9/TURB/C1,C2,CD,SQRTCD,CD25,ECONST,CTAUTW,CYPTW,TAUTW1(22)         CEL00310
     9,TAUTW2(22),YPUST1(22),YPUST2(22)                                 CEL00320
     9,TAULW(22),XPUSLW(22),CTAULW,CXPLW                                CEL00330
     9,GENK(22),FACTKE,FACTED,JTKE,JTED,CAPPA                           CEL00340
     9,CPART1(484),CPART2(484),CPART3(484),CPART4(484),CPART5(484)      CEL00350
     9,CPART6(484),CPART7(484),CPART8(484),CPART9(484),CPART0(484)      CEL00360
      COMMON/PART1/OCP(484,10),ALPH(10,10,22),RP(10),DELT,TIME,NUMBER   CEL00370
     1,CNREL,COEE(484),COEN(484),COES(484),COEW(484),CPINP(10),VOLG(484)CEL00380
     1,STAN1(22,10),STAN2(22,10),STAN3(22,10),JCP1,JCP2,JCP3,JCP4,JCP5  CEL00390
     1,JCP6,JCP7,JCP8,JCP9,JCP10,KPHI,KKLAST,MONTOR(10)                 CEL00400
      COMMON/ABC/AREAE                                                  CEL00410
      DIMENSION F(3766),FF(4840),FFF(4840)                              CEL00420
      DIMENSION DIFS(22),EMUS(22),HCONS(22),RHOS(22)                    CEL00430
      EQUIVALENCE  (DIFS(2),DIFN(1)),  (EMUS(2),EMUN(1))                CEL00440
      EQUIVALENCE  (RHOS(2),RHON(1)),  (AREAE,AREAW)                    CEL00450
      EQUIVALENCE  (HCONS(2),HCONN(1)),(FF(1),CPART1(1))                CEL00460
      EQUIVALENCE  (F(1),U(1)),(OCP(1,1),FFF(1))                        CEL00470
      DIMENSION A(22),B(22)                                             CEL00480
      EQUIVALENCE(A(1),AN(1)),(B(1),AS(1))                              CEL00490
      JPHI=LPHI                                                         CEL00500
30    CONTINUE                                                          CEL00510
COMMENT...AE,AW,AN,AS ARE USED AS TEMPORARY STORAGES, VALUES THERE      CEL00520
COMMENT...SHOULD BE APPROPRIATELY TRANSFERRED IN THE CALLING SUBROUTINE CEL00530
C---------------------- FACTORS TO ACCOUNT FOR EFFECTS OF END           CEL00540
C---------------------- BOUNDARIES (EAST AND WEST)                      CEL00550
```

```
      BWW=0.5
      BEW=0.5
      IF(IX.EQ.2) BWW=1.
      IF(IX.EQ.NXM1) BEW=0.
      BWE=1.-BWW
      BEE=1.-BEW
C---------------------- ALL FOUR CELL WALLS
      ICONST=IX1NY+IZERO(JPHI)
      I=NODEF1+ICONST
      AS(NODEF)=F(I)
      IF(NODEF.GT.2) AS(NODEF)=0.5*(F(I)+F(I+1))
      DO 31 IY=NODEF,NODEL
      I=IY+ICONST
      IN=I+1
      IE=I+NY
      IW=I-NY
      AN(IY)=0.5*(F(I)+F(IN))
      AW(IY)=BWW*F(IW)+BWE*F(I)
31    AE(IY)=BEW*F(I)+BEE*F(IE)
      IF(NODEL.LT.NYM1) RETURN
C---------------------- CORRECT AN FOR THE LAST CELL
      IN=NODEL+ICONST
      AN(NODEL)=F(IN)
      RETURN
      END
```

```
      SUBROUTINE BOUND(LPHI)                                              BOU00010
      COMMON                                                              BOU00020
     1/CASE1/UINLET,FLOWIN,RPIPE,XPIPE,FXSTEP,HINLET,HWALL                BOU00030
     2/DNY/ DYG(22),DYV(22),FV(22),FVNODE(22),R(22),RDYG(22),RDYV(22)     BOU00040
     2,RSYG(22),RSYV(22),RV(22),RVCB(22),SYG(22),SYV(22),Y(22),YV(22)     BOU00050
     3/DNYONX/AE(22),AN(22),AP(22),AS(22),AW(22),C(22),D(22),DIFE(22)     BOU00060
     3,DIFN(22),DUW(22), DIFW(22),DU(22),DV(22),EMUE(22),EMUN(22)         BOU00070
     3         ,EMUW(22),HCONE(22),HCONN(22),          HCONW(22)          BOU00080
     3,PHIOLD(22),RHOE(22),RHON(22),        RHOW(22),SP(22),SU(22)        BOU00090
     3,VOLUME(22),CONN(22),CONS(22),CONE(22),CONW(22),ESMPHI(22)          BOU00100
     4/DNX/ DXG(22),DXU(22),FU(22),FUNODE(22),KOUNT(22),RDXG(22)          BOU00110
     4,RDXU(22),RSXG(22),RSXU(22),STORE(22),SXG(22),SXU(22),X(22),XU(22)BOU00120
     5/DJPHI/ IEW(10),ILAST(10),IMON(10),IXNY(10),IZERO(10)               BOU00130
     5,JGROUP(10),KADSOR(10),KSOLVE(10),KRS(10),RELAX(10),RSREF(10)       BOU00140
     5,RSSUM(10),ITITLE(10),KTITLE(10),KEW(10),KLAST(10),KZERO(10)        BOU00150
      COMMON                                                              BOU00160
     6/DO/CCHECK,DP,FLOWPC,FLOWST,FLOWUP,GREAT,ILINE,IPLRS,IPREF,IPRINT   BOU00170
     6,ISTEP ,IX,IX1NY,IX1NY1,IX2NY2,IXMON,IXP1,IXPREF,IYMON,IYPREF       BOU00180
     6,JEMU,JH,JLAST,JLIM1,JLIM2,JLIM3,JLIM4,JP,JPP,JRHO                  BOU00190
     6,JU,JV,JVP1,KINPRI,KMPA,KRAD,KRHOMU,KTEST,LABPHI                    BOU00200
     6,LASTEP,LINEF,LINEL,NEQ,NEOP1                                       BOU00210
     6,NODEF,NODEF1,NODEL,NODEL1,NODLP1,NTDMA,NUMCOL                      BOU00220
     6,NX,NXMAX,NXM1,NXM2,NXYG,NXYP,NXYU,NXYV                             BOU00230
     6,NY,NYMAX,NYM1,NYM2,PI,RSCHEK,RSMAX,TINY                            BOU00240
      COMMON/PROP/EMUREF,PRL(10),PRT(10),RHOREF                           BOU00250
      COMMON/D2D1/ARSL(22,10),RSLINE(22,10)                               BOU00260
      COMMON/D2D2/U(462),V(462),TKE(484),TED(484),H(484),PP(22),P(400)    BOU00270
     7,RHO(484),EMU(484)                                                  BOU00280
     7,INLY(10),IOUT(10),KIN,KOUT,RELTKE,RELTED,ISTCH                     BOU00290
      COMMON                                                              BOU00300
     9/TURB/C1,C2,CD,SQRTCD,CD25,ECONST,CTAUTW,CYPTW,TAUTW1(22)           BOU00310
     9,TAUTW2(22),YPUST1(22),YPUST2(22)                                   BOU00320
     9,TAULW(22),XPUSLW(22),CTAULW,CXPLW                                  BOU00330
     9,GENK(22),FACTKE,FACTED,JTKE,JTED,CAPPA                             BOU00340
     9,CPART1(484),CPART2(484),CPART3(484),CPART4(484),CPART5(484)        BOU00350
     9,CPART6(484),CPART7(484),CPART8(484),CPART9(484),CPART0(484)        BOU00360
      COMMON/PART1/OCP(484,10),ALPH(10,10,22),RP(10),DELT,TIME,NUMBER     BOU00370
     1,CNREL,COEE(484),COEN(484),COES(484),COEW(484),CPINP(10),VOLG(484)BOU00380
     1,STAN1(22,10),STAN2(22,10),STAN3(22,10),JCP1,JCP2,JCP3,JCP4,JCP5    BOU00390
     1,JCP6,JCP7,JCP8,JCP9,JCP10,KPHI,KKLAST,MONTOR(10)                   BOU00400
      COMMON/ABC/AREAE                                                    BOU00410
      DIMENSION F(3766),FF(4840),FFF(4840)                                BOU00420
      DIMENSION DIFS(22),EMUS(22),HCONS(22),RHOS(22)                      BOU00430
      EQUIVALENCE (DIFS(2),DIFN(1)), (EMUS(2),EMUN(1))                    BOU00440
      EQUIVALENCE (RHOS(2),RHON(1)), (AREAE,AREAW)                        BOU00450
      EQUIVALENCE (HCONS(2),HCONN(1)),(FF(1),CPART1(1))                   BOU00460
      EQUIVALENCE (F(1),U(1)),(OCP(1,1),FFF(1))                           BOU00470
      DIMENSION A(22),B(22)                                               BOU00480
      EQUIVALENCE(A(1),AN(1)),(B(1),AS(1))                                BOU00490
CHAPTER 1  1  1  1  1    PRELIMINARIES    1  1  1  1  1  1  1  1  1  1  BOU00500
      JPHI=LPHI                                                           BOU00510
      IF(KPHI.EQ.JCP1) GO TO 10                                           BOU00520
      IF(KPHI.EQ.JCP2) GO TO 20                                           BOU00530
      IF(KPHI.EQ.JCP3) GO TO 30                                           BOU00540
      IF(KPHI.EQ.JCP4) GO TO 40                                           BOU00550
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      IF(KPHI.EQ.JCP5) GO TO 50                                         BOU00560
      IF(KPHI.EQ.JCP6) GO TO 60                                         BOU00570
      IF(KPHI.EQ.JCP7) GO TO 70                                         BOU00580
      IF(KPHI.EQ.JCP8) GO TO 60                                         BOU00590
      IF(KPHI.EQ.JCP9) GO TO 90                                         BOU00600
      IF(KPHI.EQ.JCP10) GO TO 100                                       BOU00610
      RETURN                                                            BOU00620
C                                                                       BOU00630
C                                                                       BOU00640
   10 CONTINUE                                                          BOU00650
      IF(IX.NE.2) RETURN                                                BOU00660
      DO 11  IY=1,NYM1                                                  BOU00670
      I=IY+IX1NY                                                        BOU00680
      IW=I-NY                                                           BOU00690
   11 CPART1(IW)=CPART1(I)                                              BOU00700
      RETURN                                                            BOU00710
C                                                                       BOU00720
C                                                                       BOU00730
   20 CONTINUE                                                          BOU00740
      IF(IX.NE.2) RETURN                                                BOU00750
      DO 21  IY=1,NYM1                                                  BOU00760
      IW=I-NY                                                           BOU00770
   21 CPART2(IW)=CPART2(I)                                              BOU00780
      RETURN                                                            BOU00790
C                                                                       BOU00800
C                                                                       BOU00810
   30 CONTINUE                                                          BOU00820
      IF(IX.NE.2) RETURN                                                BOU00830
      DO 31  IY=1,NYM1                                                  BOU00840
      I=IY+IX1NY                                                        BOU00850
      IW=I-NY                                                           BOU00860
   31 CPART3(IW)=CPART3(I)                                              BOU00870
      RETURN                                                            BOU00880
C                                                                       BOU00890
C                                                                       BOU00900
   40 CONTINUE                                                          BOU00910
      IF(IX.NE.2) RETURN                                                BOU00920
      DO 41  IY=1,NYM1                                                  BOU00930
      I=IY+IX1NY                                                        BOU00940
      IW=I-NY                                                           BOU00950
   41 CPART4(IW)=CPART4(I)                                              BOU00960
      RETURN                                                            BOU00970
C                                                                       BOU00980
C                                                                       BOU00990
   50 CONTINUE                                                          BOU01000
      IF(IX.NE.2) RETURN                                                BOU01010
      DO 51  IY=1,NYM1                                                  BOU01020
      I=IY+IX1NY                                                        BOU01030
      IW=I-NY                                                           BOU01040
   51 CPART5(IW)=CPART5(I)                                              BOU01050
      RETURN                                                            BOU01060
C                                                                       BOU01070
C                                                                       BOU01080
   60 CONTINUE                                                          BOU01090
      IF(IX.NE.2) RETURN                                                BOU01100
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      DO 61  IY=1,NYM1                                                  BOU01110
      I=IY+IX1NY                                                        BOU01120
      IW=I-NY                                                           BOU01130
   61 CPART6(IW)=CPART6(I)                                              BOU01140
      RETURN                                                            BOU01150
C                                                                       BOU01160
C                                                                       BOU01170
   70 CONTINUE                                                          BOU01180
      IF(IX.NE.2) RETURN                                                BOU01190
      DO 71  IY=1,NYM1                                                  BOU01200
      I=IY+IX1NY                                                        BOU01210
      IW=I-NY                                                           BOU01220
71    CPART7(IW)=CPART7(I)                                              BOU01230
      RETURN                                                            BOU01240
C                                                                       BOU01250
C                                                                       BOU01260
80    CONTINUE                                                          BOU01270
      IF(IX.NE.2) RETURN                                                BOU01280
      DO 81  IY=1,NYM1                                                  BOU01290
      I=IY+IX1NY                                                        BOU01300
      IW=I-NY                                                           BOU01310
81    CPART8(IW)=CPART8(I)                                              BOU01320
      RETURN                                                            BOU01330
C                                                                       BOU01340
C                                                                       BOU01350
90     CONTINUE                                                         BOU01360
      IF(IX.NE.2) RETURN                                                BOU01370
      DO 91  IY=1,NYM1                                                  BOU01380
      I=IY+IX1NY                                                        BOU01390
      IW=I-NY                                                           BOU01400
91    CPART9(IW)=CPART9(I)                                              BOU01410
      RETURN                                                            BOU01420
C                                                                       BOU01430
C                                                                       BOU01440
100   CONTINUE                                                          BOU01450
      IF(IX.NE.2) RETURN                                                BOU01460
      DO 101  IY=1,NYM1                                                 BOU01470
      I=IY+IX1NY                                                        BOU01480
      IW=I-NY                                                           BOU01490
101   CPART0(IW)=CPART0(I)                                              BOU01500
      RETURN                                                            BOU01510
      END                                                               BOU01520
```

References

1) K. Nakanishi, J. Szekely, C.W. Chang, Iron making and Steel making (Quarterly) 1975 2 p. 115.

2) K. Nakanishi, J. Szekely, T. Fujii, et al., Met. Transaction 1975, 6B, p. 111.

3) K. Nakanishi, J. Szekely, Met. Transaction, 1975, 6B, p. 245.

4) K. Kinoshita, K. Nakanishi, Tetsu-to-Hagane, 1971, 57, p. 419.

5) K. Nakanishi, J. Szekely, Trans. ISIJ, 1975, 15, p. 522.

6) J.O. Hinze, "Turbulence, 2nd Edition" 1979, McGraw-Hill, New York

7) I. Komasawa, R. Kuboi, T. Otake, Chemical Eng. Sci., 1974, 29, p. 641.

8) R. Kuboi, I. Komasawa, T. Otake, Chemical Eng. Sci., 1974, 29, p. 651.

9) R. Kuboi, I. Komasawa, T. Otake, Chemical Eng. Sci., 1974, 29, p. 659.

10) Y.H. Pao, The Physics of Fluids, 1965, 8, p. 1063.

11) R.L. Peskin, "Proceedings of Heat Transfer and Fluid Mechanics Institute", Stanford, U.P., Stanford.

12) S.L. Soo, "Fluid Dynamics of Multiphase System", Ginn Blaisdel, Waltham, Mass., 1967.

13) N. Sano, S. Shiomi, Y. Matsushita, Tetsu-to-Hagane, 1965, 51, p. 19.

14) E.T. Turkdogan, J. of The Iron and Steel Institute, 1972, 210 p. 21.

15) E.T. Turkdogan, J. of The Iron and Steel Institute, 1966, 204, p. 914.

16) T.B. Braun, J.F. Elliott, M.C. Flemings, Met. Transaction, 1979, 10B, p. 71.

17) T.B. Braun, Ph.D. Thesis, "Formation and Clustering of Alumina Particles in Liquid Iron", 1974, M.I.T., Cambridge, MA

18) E.T. Turkdogan, Trans. AIME, 1965, 233, p. 2100.

19) U. Lindborg, K. Torssell, Trans. AIME, 1968, 242, p. 94.

20) Y. Miyashita, Res. Rep., 1968, Nippon Kokan, Japan.

21) A. Engh, N. Lindskog, Scan. J. Metallurgy, 4, 1975, p. 49.

22) S. Linder, Scan. J. Metallurgy, 3, 1974, p. 137.

23) N. Lindskog, H. Sandberg, Scan. J. of Metallurgy, 2, 1973, p. 71.

24) S. Linder, "Scaninject", Jernkontoret, 1977, Lulea, Sweden

25) R. Gunn, Science, 1965, 150, p. 695.

26) P.G. Saffman, J.S. Turner, J. Fluid Mech., 1956, 1, p. 16.

27) H.M. Hulburt, S. Katz, Chemical Eng. Sci., 1964, 19, p. 555.

28) C.A. Coulaloglou, L.L. Taularides, Chemical Eng. Sci., 1977, 32, p. 1289.

29) K.J. Valentas, N.R. Amandson, I & E.C Fundamentals, 1966, 5, p. 533.

30) K.J. Valentas, O. Bilous, N.R. Amandson, I & E.C Fundamentals, 1966, 5, p. 271.

31) Smoulchowski, A., Phys. Chem. 1917, 92, p. 129.

32) V.G. Levich "Physicochemical Hydrodynamics" 1962, Prentice-Hall, Englewood Cliff, N.J.

33) P.G. Saffman, J. of Fluid Mech., 1965, 22, p. 385.

34) P.O. Rouhiainear, J.W. Stachiewicz, J. of Heat Transfer, 1970, 92, p. 69.

35) S.K. Friedlander, H.F. Johnstone, Industrial and Engineering Chemistry, 1951, 49, p. 1151.

36) C.N. Davis, Proceeding of the Royal Society, London, series A, 1966, 289, p. 235.

37) C.D. Danson, E.B. Christiansen, D.L. Salt, AIChE Journal, 1966, 12, p. 589.

38) J.T. Davis, "Turbulent Phenomena" 1972, Academic Press, New York.

39) C.S. Lin, R.W. Moulton, G.L. Putnam, Inds. and Eng. Chemistry, 1953, 45, p. 636.

40) H. Schlichting "Boundary-layer Theory, 7th edition" 1979, McGraw-Hill, New York.

41) B.E. Launder, D.B. Spalding "Mathematical Models of Turbulence", 1972, Academic Press, London.

42) R.H. Pletcher "Survey of Finite-difference Strategy for Predicting Heat Transfer in Turbulent Channel Flow" in "Turbulent Forced Convection in Channels and Bundles" ed. by Skakac and D.B. Spalding, 1979, McGraw-Hill, New York.

43) R.H. Pletcher "Finite-difference Methods for Predicting Channel Flows; Turbulence Models and Some Comparison with Experimental data" ibid.

44) D.B. Spalding, "Theoretical Prediction of Single-Phase Turbulent Flow and Heat Transfer in Ducts and Rod Bundles I, II and III" ibid

45) E.R. van Driest, J. of Aero. Sci., 1956, 23, p. 1007.

46) W.M. Pun, D.B. Spalding, "A General Computer Program for Two-Dimensional Elliptic Flow", Report Number HTS/76/2, HTS, Imperical College of Science and Technology, 1976.

47) S.V. Patankar, "Numerical Heat Transfer and Fluid Flow", 1980, McGraw-Hill, New York.

48) B.E. Launder, D.B. Spalding, Computer Method in Applied Mech. and Eng. 3, 1974, p. 269.

49) J. Crank, "The mathematics of Diffusion", 1975, Clarendon Press, Oxford.

50) J. Crank, P. Nicolson, Proc. Camb. Phil. Soc. Math. Phys. Sci., 43, 1947, p. 50.

51) M.C. Flemings "Solidification Processing", 1974, McGraw-Hill, New York

52) R.K. Iyengar, W.O. Philbrook, Met. Trans., 3, 1972, p. 1823.

53) W.F. Ames, Numerical Method for Partial Differential Equations", 1977, Academic Press, New York.

54) Private communication, Nippon Steel