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A STUDY OF LIQUID MASS TRANSPORT
IN ANNULAR AIR-WATER FLOW

by

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(1958)

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ABSTRACT

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by

William D. Hinkle

Submitted to the Department of Nuclear Engineering
on May 12, 1967 in partial fulfillment of the
requirements for the degree of Doctor of Science.

In annular gas-liquid flow, liquid mass transport between the dispersed phase and the film is a result of two basic processes which are usually referred to as entrainment and deposition. The objective of the experimental work described in this thesis was to obtain fundamental information concerning these processes.

An experimental facility was designed to produce adiabatic, annular air-water flow upwards through a vertical tube with an inside diameter of 0.497 in. and an approximate length of 14 ft. In order to provide a standard entrance condition, water was introduced into the tube through a porous wall section; so that essentially all of it initially flowed as a film along the wall. Independent variables included air mass flow rate (51 to 251 lb/hr), water mass flow rate (102 to 524 lb/hr) and inlet pressure (40 to 90 psia). For a particular flow condition, the development of the liquid phase distribution resulting from the net effect of the entrainment and deposition processes was studied by measuring the dispersed water fraction as a function of distance along the tube. In addition, the variation of pressure along the tube was determined by measuring the pressure drop between the water injection section and various locations downstream.

A study was also made of the characteristics of the disturbance waves on the surface of the water film. Qualitative observations of these waves were made using a stroboscope. High speed motion pictures were also taken for several flow conditions and analyzed to obtain quantitative information concerning wave frequency, average velocity, average disturbance length, and the average fraction of the film surface covered by waves.

The experimental results showed that, for a particular experimental condition, the dispersed water fraction increased continuously along the tube. At distances greater than 60 in. downstream of the water injection section, the rate of increase along the tube was approximately constant. However, experimental measurements were limited to a distance of 130.25 in. from the water injection section. The pressure gradient was approximately constant at distances greater than 30 in. downstream of the water injection section.

Results obtained from analysis of the motion picture indicated that, for a particular flow condition, the average fraction of the film surface covered by disturbance waves decreased along the tube near the inlet. This was primarily due to a decrease in frequency caused by wave agglomeration. The latter process resulted from the fact that, for a particular flow condition, all disturbance waves did not have the same velocity. However, at distances greater than 60 in. from the water injection section, this effect was not important and the average fraction of the film surface covered by disturbance waves was approximately constant along the tube.

The analysis and correlation of the experimental results indicated that, to a good approximation, the net rate of water mass transport from the film at a particular location along the tube was proportional to the rate of energy transfer from the dispersed phase to the part of the film surface covered by disturbance waves. Except for a few values of the dispersed water fraction corresponding to the lowest air and water flow rates and to measurements made a very short distance downstream of the water injection section, the agreement between a semi-empirical equation based on this relationship and the experimental values of the dispersed water fraction was within the uncertainty expected from: (1) experimental error and (2) the uncertainty of the assumptions made in the derivation of this equation.

It is believed that experimental results such as presented in this thesis provide information which may be of value in the development of a phenomenological model of burnout, even though burnout occurs under non-adiabatic conditions.

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DEDICATION

This thesis is dedicated to the author's wife, Alice, whose help and encouragement made it possible.

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CHAPTER I

SUMMARY

1.1 Introduction

For conditions of gas-liquid flow through a vertical tube or channel, the distribution of the phases can assume one of four basic regimes - bubble, slug, semiannular and annular. The annular regime is characterized by the fact that part of the liquid flows along the tube or channel wall as a thin film while the rest is dispersed in the gas, forming a central core or dispersed phase.

In annular flow, liquid mass transport between the dispersed phase and the film is believed to be a result of two basic processes which are referred to in this study as entrainment and deposition. High speed motion pictures obtained by Hall-Taylor and Hewitt (15) have indicated that, under adiabatic conditions, the entrainment process is related to the existence of "disturbance" waves on the surface of the water film. These waves project well out into the gas, and entrainment probably results from a shearing of liquid from their crests. Liquid droplets which are entrained from the waves are dispersed and transported along with the gas by drag forces. In addition, these droplets are subject to impulses resulting from the random motion of turbulent eddies. As a result, droplets which are entrained from the film at a particular location are probably deposited on the film further downstream.

In recent years, consideration has been given to using a steam-water mixture in annular flow as a coolant for nuclear reactors. Reactors of this type have been discussed by Collier and Lacy (5) and

by Silvestri (29). This method of cooling offers the advantage over single-phase flow of greatly increased heat transfer coefficients. However, the power or heat flux is limited by the possibility of "burnout". Therefore considerable experimental and analytical work has been directed toward the development of a rational basis for predicting the occurrence of this phenomenon. The experimental work has consisted of measurements of the burnout heat flux as a function of several independent variables. Attempts to analyze and correlate the results of these measurements have used idealized models which relate the burnout condition to the heat and mass transport processes believed to be occurring. However, because of a lack of sufficient information concerning the mechanisms and rates of liquid mass transport, attempts to translate this suggestion into a useful correlation have only been partially successful.

For steam-water flow through a heated tube under conditions such that boiling is partially or completely suppressed, Hewitt (17), (18) found experimentally that burnout results from a gradual decrease of the film flow rate to zero at the end of the heated section. This probably occurs as a result of evaporation and the net effect of the entrainment and deposition processes which are observed in adiabatic flow. Therefore, experimental information concerning the entrainment and deposition processes which is obtained under adiabatic conditions should be of value in developing a phenomenological model of burnout in annular flow, even though burnout occurs under non-adiabatic conditions. The experimental work described here was conceived with this thought in mind.

1.2 Description of the Experimental Work

The primary objective of the experimental work was to measure the dispersed water fraction as a function of distance along a vertical tube for conditions of adiabatic, annular air-water flow. A standard entrance condition was provided for these measurements by introducing the water through a porous wall section so that essentially all of it would initially flow as a film along the wall. Independent variables which defined a particular flow condition included air mass flow rate, water mass flow rate, and pressure at the tube inlet.

For a particular flow condition, the variation of pressure along the tube was determined by measuring the pressure drop between the water injection section and various locations downstream. Observations were also made of the disturbance waves on the film surface using a stroboscope. In addition, motion pictures were taken for several flow conditions. The motion pictures were then analyzed to obtain quantitative information concerning wave frequency, average velocity and average disturbance length. The latter term is used in this work to indicate length of the disturbed area of the film associated with a particular wave.

1.2.1 Experimental Apparatus

The experimental apparatus consisted of a hydraulic system and motion picture equipment.

Hydraulic system.- A flow diagram of the hydraulic system is shown in Figure 3.1. Air was supplied by a non-lubricated reciprocating compressor. From the supply pipe, the air passed through a pressure regulating valve, an orifice used to measure flow rate, a heat exchanger used to regulate temperature and a filter, before

entering the test section.

Air from the top of the test section was discharged to the atmosphere through throttling valves used to regulate the flow rate. Air temperatures were measured just upstream of the inlet and at the outlet of the test section.

Water was forced into the test section from a supply tank by means of compressed air. Water from the tank passed through a filter, a flow control valve, a rotameter used to measure flow rate, a heat exchanger used to regulate temperature, another filter and into the test section. The water temperature was measured just before it entered the test section by means of a thermocouple.

The test section was a vertical tube with an inside diameter of 0.497 in. and a total length of approximately 14 ft. This tube consisted of several sections. Air entered axially through an approximately 2-1/2 ft. long section made of stainless steel tubing which served to remove any swirl motion from the air stream before it entered the water injection section. The water injection section was located just above the inlet calming section. It was 6 in. long and consisted of a porous bronze cylinder inserted into a Plexiglas Body machined to provide an annular pressure chamber as shown in Figure 3.3.

The remainder of the tube was made of seven sections having various lengths. One of these sections was designed so that the water film could be removed through another porous bronze cylinder. This made it possible to measure the dispersed water fraction as described in Section 1.2.2 below. The design of the film removal section was similar to that of the water injection section. Three of the

remaining six sections were machined from Plexiglas and could be used to observe or photograph the flow. The remaining three sections were made of stainless steel tubing. The lengths of the various sections were such that either the film removal section or a Plexiglas section could be located at any one of twenty-two 6 in. intervals above the water injection section.

Each of the sections of the test section was provided with flanges designed to avoid discontinuities at the various joints. The entire test section was vertically aligned by means of adjustable clamps.

The static pressure at the location of the water injection section was measured by means of a Bourdon gage. The pressure drop between this section and the film removal section was measured by means of a U tube manometer. In order to assure that only one phase was present in the tubing connecting the gage and manometer to the test section, a slight gas purge was maintained through the pressure taps. A pair of identical rotameters was provided to establish a visual check on the purge rates.

The mixture of air and water leaving the top of the test section was separated by means of two cyclone separators arranged in parallel. Air leaving the separators was directed to the atmosphere. Water leaving the separators was directed either to a storage tank or to a collection tank with a sight glass.

Motion picture equipment.- The camera used to obtain motion pictures of the disturbance waves on the surface of the water film was driven by a universal motor and was designed for continuous motion of the film at speeds up to 3000 frames/sec. Three 50,000 candle power

flood lamps were used. A timer was constructed which consisted of a pointer rotated in front of a marked disc by a motor. A meter stick was used as a scale. The timer speed was controlled by regulating the voltage applied to the motor.

1.2.2 Experimental Procedures

In order to carry out experimental measurements of the dispersed water fraction or pressure drop at a particular position downstream of the water injection section, the test section was arranged to locate the film removal section at the desired position. Similarly, to obtain motion pictures of disturbance waves at a particular position, the test section was arranged to locate one of the Plexiglas sections at this position.

A flow condition was established by setting the air mass flow rate, water mass flow rate, and the pressure and temperature at the test section inlet. The air mass flow rate was varied from 51 to 251 lb/hr. The water mass flow rate was varied from 102 to 524 lb/hr. The inlet pressure was varied from 40 to 90 psia. The temperatures of the air and water at the test section inlet were held constant at approximately 70°F.

For each flow condition, the dispersed water fraction and total pressure drop were determined at from 7 to 9 different positions extending to approximately 11 feet downstream of the water injection section. Motion pictures of the disturbance waves were taken for some of these conditions at 3 different positions extending to approximately 10 feet from the water injection section.

For a particular experimental condition, the dispersed water fraction at the location of the film removal section was determined

from measurements of the film and dispersed water flow rates. The film mass flow rate was measured by removing the film through the porous bronze wall using the differential pressure between the test section and the atmosphere. The water removed through the bronze was separated from the air removed along with it and drained into a collection tank. Dispersed water which was not removed through the porous wall was separated from the air leaving the test section exit and drained into another collection tank. The rate of collection in both cases was determined by observing the change in water level during a time interval measured with a stop watch.

This procedure was repeated for several values of the rate of air removal through the porous wall in order to check that the film was being completely removed. When the ratio of the dispersed water collection rate to the total collection rate was independent of the rate of air removal, it was assumed that the film was being completely removed and that this ratio was equivalent to the dispersed water fraction. Typical results are shown in Figure 3.8.

The pressure drop between the water injection section and the film removal section was measured by means of the gas purged manometer system described in Section 1.2.1. When making this measurement, the gas purge rates were regulated so that they were equal and negligible compared to the air flow rate through the test section.

For each experimental condition, a stroboscope was used to visually observe the water film. This observation was made by directing the stroboscope at the Plexiglas section immediately downstream of the water injection section and adjusting the flash frequency until it was approximately equal to the disturbance wave frequency.

In order to obtain motion pictures of the disturbance waves for a particular flow condition, the camera was focused on one of the Plexiglas sections of the test section. Once the flow condition was established, the timer was started and its speed was measured with the stroboscope just before starting the camera.

After development, the motion picture films were analyzed by projecting them onto a white card marked with evenly spaced horizontal lines. For a particular roll of film, wave frequency was measured by counting the number of waves which passed through the center of the Plexiglas section during a time interval measured by the timer. The individual velocity of a particular wave was determined by measuring the distance traveled by the wave during a time interval which was again determined by the timer. The distance measurement was made by noting the initial and final positions of the wave relative to the horizontal lines on the white card. These lines were also used to measure the disturbance length of a particular wave at a position near the center of the Plexiglas section.

1.3 Experimental Results

A typical graph of the results of measurements of the dispersed water fraction is shown in Figure 4.1.¹ From this figure, it can be observed that, for a particular flow condition, the dispersed water fraction increases continuously with distance downstream of the water injection section. However, at distances, Z , greater than 60 in.

¹ Note that symbols which appear on figures or in the text are defined in the list of nomenclature provided in Appendix I.

from the water injection section, the rate of increase with distance becomes approximately constant and the dispersed water fraction increases almost linearly along the tube. Figure 4.1 also shows the effect of air mass flow rate on the dispersed water fraction. Observations regarding this effect and the effect of water mass flow rate and inlet pressure at a particular distance are summarized below:

Independent Variable	Effect of an Increase in the Independent Variable	
	W_d/W_L	$\frac{d(W_d/W_L)}{dZ}$
Air Flow Rate	increases	increases
Water Flow Rate	increases	increases
Inlet Pressure	decreases	decreases

A typical graph of the results of measurement of pressure drop is shown in Figure 4.4. From this figure, it can be observed that, for a particular experimental condition, the pressure gradient is approximately constant at distances greater than 30 in. from the water injection section. At distances less than this the pressure gradient is somewhat higher. Figure 4.4 also shows the effect of air mass flow rate on pressure gradient. Observations regarding this effect and the effect of water mass flow rate and inlet pressure are summarized below:

Independent Variable	Effect of an Increase in the Independent Variable on Pressure Gradient
Air Flow Rate	dP/dZ increases
Water Flow Rate	dP/dZ increases
Inlet Pressure	dP/dZ decreases

Visual observations of the disturbance waves on the surface of the water film using a stroboscope showed that these waves were present immediately downstream of the porous bronze cylinder in the water injection section for each of the flow conditions studied. In the motion pictures, the disturbance waves appear as irregularly spaced areas of disturbed liquid moving along the film surface. They are therefore to be contrasted with regularly spaced sinusoidal ripples. The disturbed area of a particular wave has a "milky" appearance which probably is a result of light scattering from the ruffled surface. An enlargement of a typical frame from the motion picture films is shown in Figure 4.7.

A typical graph of the results of measurements of disturbance wave frequency is shown in Figure 4.10. From this figure, it can be observed that, for a particular flow condition, the frequency decreases along the tube. However, at distances greater than 60 in. downstream of the water injection section, the rate of decrease is small and the frequency becomes approximately constant. The motion pictures show that the decrease in frequency with length is caused by wave agglomeration. This process results from the fact that all disturbance waves do not have the same velocity. Thus, the faster waves tend to overtake the slower ones. Typical histograms of wave velocity distribution are shown in Figure 4.16.

For a particular flow condition, the average wave velocity increases along the tube. On the other hand, the average disturbance length decreases along the tube. However these variations are both small.

The effects of the independent variables on the wave

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frequency, average velocity and average disturbance length at a particular distance along the tube are summarized below:

Independent Variable	Effect of an Increase in the Independent Variable		
	Frequency	Average Velocity	Average Disturbance Length
Air Flow Rate	increases	increases	remains approx. constant
Water Flow Rate	increases slightly	increases slightly	increases
Inlet Pressure	decreases	decreases	increases slightly

1.4 Analysis and Correlation of the Experimental Results

At a given location downstream of the water injection section, it should be possible to express the rate of increase of the mass flow rate of dispersed water along the tube as follows:

$$\frac{dW_d}{dZ} = E - \Delta \quad (5-1)$$

where E is the rate of entrainment ($\text{lb}_m/\text{hr ft}$) and Δ is the rate of deposition ($\text{lb}_m/\text{hr ft}$).

For adiabatic flow conditions such as were used for the experimental work, it seems reasonable to expect that the rate of deposition would become equal to the rate of entrainment and $\frac{dW_d}{dZ}$ would decrease to zero at a sufficiently large distance downstream of the water injection section. The experimental observation that $\frac{dW_d}{dZ}$ does not decrease to zero appears to have two possible explanations:

- 1) The rate of droplet deposition is small compared to the

rate of entrainment for the range of flow conditions which were studied.

- 2) At large distances from the water injection section, the rate of deposition is proportional to, but less than the rate of entrainment.

Each of these possibilities is considered below.

The nature of the entrainment process as observed in the motion pictures suggests that the rate of entrainment should be proportional to the rate of energy transfer from the dispersed phase to the part of the film surface covered by disturbance waves. This relationship is expressed mathematically as follows:

$$E = B_o \tau_i \Pi D_c (V_c - V_f) N_w \quad (5-6)$$

where B_o is a constant of proportionality, τ_i is the interfacial shear stress (lb_f/ft^2), D_c is the diameter of the core of the tube occupied by the dispersed phase (ft), $(V_c - V_f)$ is the difference between the average velocity of the dispersed phase and the average film velocity (ft/hr), and N_w is the average fraction of the film surface covered by disturbance waves (ft^2 of disturbance area/ ft^2 of film surface). The product, $\tau_i (V_c - V_f)$ is the net rate of energy transfer from the dispersed phase per unit area of the film surface.

Assuming that the gravitational and acceleration forces are small compared to the interfacial shear force, this force can be approximately related to the total pressure gradient by the following expression:

$$\tau_i \approx \left| \frac{dP}{dz} \right| \frac{D_c}{4} \quad (5-9)$$

In annular flow, the average velocity of the liquid film

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is usually small compared with the average velocity of the dispersed phase. In addition, the average velocity of the dispersed phase is approximately equivalent to the average velocity of the gas. Therefore, to a first approximation, it should be possible to write the difference between the average velocity of the dispersed phase and the average film velocity as follows:

$$(V_c - V_f) \simeq V_G \quad (5-10)$$

Then, using the perfect gas law, $(V_c - V_f)$ can be expressed in terms of the air mass flow rate, pressure, and temperature by the following equation:

$$(V_c - V_f) \simeq RT \frac{W_G}{P \frac{\pi D_c^2}{4}} \quad (5-13)$$

Since the disturbance waves in annular flow almost always are symmetrical around the circumference of the tube, it should be possible to express the average fraction of the film surface covered by these waves in terms of frequency, mean velocity and mean disturbance length as follows:

$$N_W \simeq \left(\frac{FL}{V_W} \right) \quad (5-14)$$

The values of measurements of disturbance wave frequency, average velocity, and average disturbance length obtained from analysis of the motion pictures were used to calculate values of $\left(\frac{FL}{V_W} \right)$. To a first approximation, the results of these calculations can be correlated by the following equation:

$$\left(\frac{FL}{V_W} \right) = B_4(Z) W_L^{0.5} \quad (5-17)$$

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where $B_4(Z)$ is a quantity which is only a function of distance from the water injection section.

Values of $B_4(Z)$ are shown graphically in Figure 5.6. The solid line is drawn through the average value of $B_4(Z)$ at each of the three positions along the tube. Since, for a particular flow condition, the average velocity and disturbance length of the waves are approximately independent of distance from the water injection section, the decrease of $B_4(Z)$ along the tube is primarily due to the decrease in wave frequency caused by the agglomeration process.

Equations (5-6), (5-9), (5-13), (5-14) and (5-17) can be combined to give the following expression for the rate of entrainment:

$$E = B_3 B_4(Z) \left| \frac{dP}{dZ} \right| \frac{W_G}{P} W_L^{0.5} \quad (5-18)$$

where B_3 is a quantity which should be approximately independent of flow condition and distance along the tube.

If the rate of deposition of dispersed water, Δ , is small compared to the rate of entrainment, Equations (5-1) and (5-18) can be combined and rearranged to give the following expression:

$$\frac{\frac{dW_d}{dZ} P}{\left| \frac{dP}{dZ} \right| W_G W_L^{0.5}} = B_3 B_4(Z) \quad (5-21)$$

Calculated values of the left side of this equation are shown in Figure 5.7.

According to Equation (5-21) the ratio of the expression on the left side to $B_4(Z)$ is equal to B_3 which should be approximately constant along the tube. However, a comparison of Figures 5.6 and 5.7 shows that this ratio varies by at least a factor of three along

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the tube. Therefore, it seems reasonable to conclude that the assumption that the rate of deposition is small compared to the rate of entrainment is not valid. However, Figure 5.7 shows that values of the expression on the left side of Equation (5-21) calculated for several different experimental conditions are approximately the same at a given distance from the inlet. Therefore, to a first approximation, the rate of increase of the mass flow rate of dispersed water with distance along the tube can be expressed as follows:

$$\frac{dW_d}{dz} = B_5(Z) \left| \frac{dP}{dz} \right| \frac{W_G}{P} W_L^{0.5} \quad (5-22)$$

and Figure 5.7 can be considered to be a graph of values of $B_5(Z)$. The equation of the solid line in this figure has been determined empirically. The result is the following:

$$B_5(Z) = 0.070 + 0.72e^{-Z/17.65} \quad (5-23)$$

Equations (5-22) and (5-23) can be combined and the resulting expression approximately integrated from $Z = 0$ to a distance downstream of the water injection section. When this is done and both sides of the resulting expression are divided by W_L , the following expression is obtained for the dispersed water fraction:

$$\frac{W_d}{W_L} = \frac{W_G}{W_L^{0.5}} \frac{\left| \ln P/P_1 \right|}{Z} \left[0.070 + 12.8 \left(1 - e^{-Z/17.65} \right) \right] \quad (5-25)$$

Equation (5-25) was used to calculate values of the dispersed water fraction for each of the flow conditions for which this quantity was measured in the present experiments. The results of this calculation are compared with the corresponding experimental results in Figures 5.11 and 5.13. Figure 5.11 and 5.13 show that

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most of the experimental values of the dispersed water fraction are within 30 per cent of the value predicted by Equation (5-25). For values of the dispersed water fraction greater than 0.10, the agreement is better than this. On the other hand, some values of the dispersed water fraction less than 0.10 are not within 30 per cent of the value predicted by Equation (5-25). In general, the latter data points correspond to the lowest air and water flow rates or to measurements made a short distance downstream of the water injection section.

1.5 Comparison of the Experimental Results with Results Obtained by Others

The comparison of Equation (5-25), which was semi-empirically derived from the experimental values of the dispersed water fraction obtained from the present work, with experimental results previously reported by Gill, et al. (12) and with experimental results recently reported by Cousins, et al. (8) indicates that, for a particular flow condition, the rate of increase of the dispersed water fraction with distance along the tube is a function of Z/D rather than Z . This observation leads to the development of the following equation for the dispersed water fraction which includes the effect of the tube diameter:

$$\frac{W_d}{W_L} = \frac{W_G}{W_L}^{0.5} \frac{[\ln P/P_1]}{Z/D} \left[0.070 Z/D + 25.6 \left(1 - e^{-Z/35.5D} \right) \right] \quad (6-9)$$

For a tube diameter of 0.497 in., this equation reduces to Equation (5-25).

The experimental results reported by Gill are in good agreement with Equation (6-9) and therefore with the results obtained from

the present experiments. However, experimental results reported by Cousins, et al. (8) are consistently lower than predicted by Equation (6-9) and are therefore not in agreement with the results obtained from the present experiments or the results reported by Gill.

1.6 Conclusions and Recommendations

The experimental results show that, for a particular experimental condition, the dispersed water fraction at distances greater than 120 diameters downstream of the water injection section increases almost linearly along the tube. It is believed that this result indicates that, under these conditions, the rate of deposition is proportional to but less than the rate of entrainment and both rates remain approximately constant along the tube. Although the experimental results obtained in this study were limited to a distance of 262 diameters downstream of the water injection section, similar experimental results were recently obtained by Cousins, et al. (8) for distances extending to 576 diameters downstream of the water injection section.

Except for a few values of the dispersed water fraction corresponding to the lowest air and water flow rates or to measurements made a very short distance downstream of the water injection section, the agreement between experimental values of the dispersed water fraction obtained in the present study and Equation (5-25) is believed to be within the uncertainty which results from: (1) the assumptions made in the derivation of this equation, (2) the uncertainty of the experimental results used to determine the empirical constants and (3) the uncertainty of the values of W_G , W_L , P_1 , and P which correspond to a particular flow condition and distance from

the water injection section.

The experimental results show that the mass flow rate of dispersed water does not approach an equilibrium value for a wide range of flow conditions and tube lengths of practical interest. Therefore, in the case of burnout experiments which utilize two-phase inlet conditions, the value of this quantity at the inlet of the heated section would probably depend on the method used to initially mix the steam and water upstream of this location. This means that the burnout data obtained in such experiments would probably not be independent of the experimental apparatus.

The experimental results described here and similar results reported by Gill, et al. (12) and Cousins, et al. (8) show that, in adiabatic air-water flow, a considerable distance is required for the net rate of liquid mass transport from the film to reach an approximately constant value for a particular flow condition. Therefore, since in non-adiabatic flow, the steam and water mass flow rates are changing continuously along the tube, it seems unlikely that the net rate of liquid mass transport from the film at a particular location along the heated length would correspond to the equilibrium value for the same flow condition under adiabatic conditions. However, the analysis and correlation of the experimental results indicates that, to a good approximation, the net rate of water mass transport from the film at a particular location along the tube is proportional to the rate of energy transfer from the air to the part of the film surface covered by disturbance waves. Therefore it should, in principle, be possible to use this relationship to determine local rates of liquid mass transport from the film in non-adiabatic flow.

It is recommended that future study be directed toward obtaining a basic understanding of the following aspects of annular gas-liquid flow:

- 1) The wave structure at the interface between the liquid film and the dispersed phase.
- 2) Turbulent eddy transport of dispersed droplets.

Information of this type should be of considerable value in the development of a phenomenological model of burnout for non-adiabatic annular flow.

CHAPTER II

INTRODUCTION

2.1 Background and Motivation

When a mixture of gas and liquid flows through a vertical tube or channel, the spatial distribution of the two phases can assume four basic configurations or regimes. These regimes are shown in Figure 2.1. The study presented in this thesis is concerned with the annular flow regime.¹ This regime is characterized by the fact that part of the liquid flows along the tube or channel wall as a thin film under the influence of the faster moving gas. The rest of the liquid is dispersed in the gas, forming a central core or dispersed phase.

In recent years, consideration has been given to using a steam-water mixture in annular flow as a coolant for nuclear reactors. Reactors of this type have been discussed by Collier and Lacy (5) and by Silvestri (29). This method of cooling offers the advantage over single-phase flow of greatly increased heat transfer coefficients. However, the power or heat flux is limited by the possibility of the occurrence of "burnout." This phenomenon is characterized by a sudden decrease in the local heat transfer coefficient and can cause overheating and physical damage of the heated surface.²

¹This flow regime has been referred to by some authors as "dispersed-annular flow," "climbing film flow," "fog flow," and "spray flow."

²A discussion of burnout for conditions of steam-water flow through a uniformly heated tube is given in Appendix A.

BUBBLE FLOW **SLUG FLOW** **SEMIANNULAR FLOW** **ANNULAR FLOW**

FIGURE 2.1
FLOW REGIMES FOR GAS-LIQUID FLOW THROUGH
A VERTICAL TUBE

Considerable experimental and analytical work has been directed by many investigators towards the development of a rational basis for predicting the occurrence of burnout. The experimental work has consisted of measurements of the burnout heat flux as a function of several independent variables. Attempts to correlate the results of these measurements have utilized the following methods:

- 1) For a particular range of experimentally tested flow conditions, the experimental data are used to empirically establish conservative design limits.
- 2) For a particular range of experimentally tested flow conditions, statistical theory is used to develop a functional relationship between measured values of the burnout heat flux and the independent variables.
- 3) Equations describing the burnout condition in terms of the hydrodynamic and heat and mass transport processes believed to be occurring are used to develop a general relationship between the burnout heat flux and the independent variables.

Examples of the use of the first of these methods are the work of DeBortoli (10) and the work of Janssen and Levy (22). An example of the use of the second method is the work of Jacobs and Merrill (21). Correlations such as these have considerable practical value. However, they have the serious limitation of not being safely applicable beyond the range of experimental conditions upon which they are based. Therefore, many investigators have attempted to use the third method.

One of the first correlations obtained using the third method was proposed by Zuber (35), who assumed that burnout was caused by a local transition from nucleate to film boiling. The trends predicted by this correlation were in good agreement with burnout data obtained for subcooled and low quality conditions for which the flow regime is probably bubble flow. However, these trends were not in good agreement with burnout data obtained for medium and high quality conditions. As a result of this difficulty, other investigators such as Isbin, et al. (20) and Hewitt, et al. (17) (18) have suggested that, for medium and high quality steam-water flow, the flow regime is predominantly annular flow and burnout results from a loss of the liquid film by liquid mass transport and evaporation. However, because of a lack of sufficient information concerning the mechanisms and rates of liquid mass transport, attempts to translate this suggestion into a useful correlation have only been partially successful. Thus, it has become clear that experimental research providing such information is needed. This fact provided the motivation for this thesis.

2.2 Liquid Mass Transport Processes in Annular Gas-Liquid Flow

In annular gas-liquid flow, liquid mass transport between the dispersed phase and the film is probably a result of two basic processes. These processes will be referred to in this thesis as entrainment and deposition.

High speed motion pictures of annular air-water flow obtained by Hall-Taylor and Hewitt (15) have indicated that, under adiabatic conditions, the entrainment process is related to the

existence of "disturbance" waves on the surface of the water film. These waves probably develop as a result of hydrodynamic instability caused by the relative motion between the gas and the slower-moving liquid film.³ Since they project well out into the gas core, it is believed that entrainment results from a shearing of liquid from their crests by the gas.

Liquid droplets which are entrained from the film are dispersed and transported along with the gas by drag forces acting in the direction of the flow. In addition, experimental results such as those obtained by Alexander and Coldren (1) indicate that these droplets are subject to random impulses resulting from the motion of turbulent eddies. As a result, droplets which are entrained from the film at a particular location are probably deposited on the film further downstream.

For steam-water flow through a heated annulus, Hewitt, et al. (17) observed that entrainment also occurs when bubbles formed as a result of nucleate boiling break through the film surface. However, Hewitt also observed that boiling was usually suppressed near the exit end of the heated section. This phenomenon is probably caused by the fact that, in annular flow, the thickness and temperature of the laminar sublayer of the liquid film is often insufficient to support fully developed nucleate boiling. Under these conditions, Hewitt found that burnout resulted from a gradual decrease of the film flow rate to zero at the end of the heated section. This

³A theoretical discussion of instabilities of this type is given by Chandrasekhar (4).

probably occurred as a result of evaporation and the net effect of the entrainment and deposition processes which are observed in adiabatic flow. Therefore, experimental information concerning the entrainment and deposition processes which is obtained under adiabatic conditions should be of value in developing a phenomenological model of burnout in annular flow, even though burnout occurs under non-adiabatic conditions.

2.3 Basis of the Experiments

For adiabatic, annular gas-liquid flow through a vertical tube, under conditions such that disturbance waves are present on the surface of the liquid film, the net rate of liquid transport from the film to the dispersed phase at a particular location should be equal to the difference between the rate of entrainment and the rate of deposition. Therefore, it should be possible to utilize experimental measurements of the dispersed liquid fraction as a function of distance along the tube to obtain quantitative information concerning these processes. The experiments described in this thesis were conceived with this thought in mind.

2.4 Previously Reported Experimental Results

Prior to the beginning of the experimental work described in this thesis, an experimental measurement of the type described above was reported by Gill, et al. (12). This experiment was focused on a single flow condition for air-water flow upwards through a vertical tube. The tube had an inside diameter of 1.25 in. and was 22 ft long. Air was forced through it from the bottom. A calming section, approximately 6 ft in length, was provided between the air inlet and the

position of water injection. The water was injected through a porous bronze wall section designed to cause little or no adventitious entrainment. The air and water mass flow rates were held constant at 500 lb/hr and 1000 lb/hr respectively. The inlet pressure was 26.9 psia. The air and water temperatures were approximately equal to the ambient temperature.

Dispersed water mass velocity profiles were obtained at 12 different positions extending to 17.5 ft downstream of the water injection section. This was done using a traversing, water collection probe. These profiles were used to determine the total mass flow rate of dispersed water as a function of distance from the inlet. This was done by numerically integrating each profile from the center of the tube out to an arbitrary radial position 0.1 in. from the wall. Near this radial position, the mass velocity profiles indicated a sharp rise in the water mass velocity. This was taken to indicate that the collection probe was contacting the waves on the surface of the film. The results are shown in Figure 2.2 as a graph of the dispersed water fraction as a function of distance downstream of the water injection section. This graph shows that, at 17.5 ft from the water injection section, the dispersed water fraction was still increasing. However, since the rate of increase appeared to decrease gradually along the tube, it was believed that, if the tube had been long enough, this quantity would have eventually become constant.

The pressure drop between the water injection section and various positions downstream was also measured. This was done using a liquid purged manometer system. The results of these measurements are shown in Figure 2.3. This graph shows that the pressure gradient

FIGURE 2.2

VARIATION OF DISPERSED WATER FRACTION WITH DISTANCE
ALONG A VERTICAL TUBE (GILL, et al.12)

FIGURE 2.3
 VARIATION OF TOTAL PRESSURE DROP WITH DISTANCE ALONG A
 VERTICAL TUBE (GILL, et al. 12)

was highest near the inlet but decreased along the tube and became approximately constant at distances greater than 5 ft downstream of the water injection section. This result suggested that entrance effects related to changes in the velocity distribution of the dispersed phase, acceleration of the liquid film, development of the disturbance waves, etc. were not significant beyond this distance.

CHAPTER III

DESCRIPTION OF THE EXPERIMENTAL WORK

3.1 General

The primary objective of the experimental work was to measure the dispersed water fraction as a function of distance along a vertical tube for conditions of adiabatic, annular air-water flow. A standard entrance condition was provided for these measurements by introducing the water through a porous wall section so that essentially all of it would initially flow as a film along the wall. Independent variables which defined a particular flow condition included air mass flow rate, water mass flow rate, and pressure at the tube inlet.

The variation of pressure along the tube for a particular flow condition was determined by measuring the pressure drop between the water injection section and various locations downstream.

In order to provide information which could be used in the analysis and correlation of the measurements of dispersed water fraction, an experimental study was also made of the characteristics of the disturbance waves on the surface of the water film. Qualitative observations of these waves were made using a stroboscope. In addition, motion pictures were taken for several flow conditions. The motion pictures were then analyzed to obtain quantitative information concerning wave frequency, average velocity, and average disturbance length. The latter term is used in this thesis to indicate the length of the disturbed area of the film associated with a particular disturbance wave. See Figures 4.7 through 4.9 in Chapter IV.

3.2 Experimental Apparatus

The experimental apparatus consisted of a hydraulic system and motion picture equipment. The discussion which follows is a general description of this apparatus. Additional details and calibration information are given in Appendix C.

3.2.1 The Hydraulic System

The hydraulic system was designed to produce the desired flow conditions and to provide the instrumentation needed to measure the dispersed water fraction and pressure drop. A flow diagram is shown in Figure 3.1.

1. Air supply apparatus.- Air was supplied to the hydraulic system from a non-lubricated, reciprocating compressor capable of delivering up to 450 scfm of air at 100 psig. From the supply pipe, the air first passed through a pressure regulating valve which was used to adjust the pressure at the inlet to the test section. The air then flowed through a thin plate orifice mounted between special flanges in a straight section of steel pipe. Pressure taps were located in the flanges just upstream and downstream of the orifice. The air pressure and temperature at the orifice inlet and the pressure drop across the orifice were measured respectively with a Bourdon gage, a thermocouple and a well-type manometer. Next, the air flowed through a shell-and-tube heat exchanger used as a cooler. City water was used as the coolant on the shell side in a single pass to a drain. The cooling water flow rate was regulated by means of a needle valve located on the inlet side. From the cooler, the air flowed through a filter and into the test section. Air from the top of the test

3-3

FIGURE 3.1 FLOW DIAGRAM OF THE HYDRAULIC SYSTEM

3-4

section was directed through two cyclone separators arranged in parallel, before being discharged to the atmosphere through either or both of two throttling valves. One of these valves was a globe valve and was used for coarse adjustment of the air flow rate. The other was a needle valve and was used for fine adjustment. Air temperatures were measured just upstream of the inlet to the test section and at the outlet of the separators by means of thermocouples.

2. Water supply apparatus.- Water was forced into the test section from a 60 gallon supply tank by means of compressed air supplied by two oil-lubricated, reciprocating compressors connected in parallel. These compressors were capable of delivering up to approximately 50 scfm of air at 95 to 120 psig. With this capacity, it was possible to establish water flow rates of at least 1 gpm.

Air from the compressors flowed through a filter and pressure regulating valve before entering the water tank. Water from the tank passed first through a filter and then through a rotameter used to measure the flow rate. The flow rate was regulated by means of a globe valve located on the inlet side of the rotameter. From the rotameter, the water flowed through a shell-and-tube heat exchanger used as a cooler. City water was used as the coolant on the shell side in a single pass to a drain. The cooling water flow rate was regulated by means of a needle valve located on the inlet side of the heat exchangers. From the cooler, the water flowed through another filter and into the test section. The water temperature was measured just before it entered the test section by means of a thermocouple.

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3. Test section.-- The test section was a vertical tube with an inside diameter of 0.497 in. and a total length of approximately 14 ft. This tube consisted of several sections as shown in Figure 3.2. Detailed drawings of these sections are shown in Figures C.5 through C.9 of Appendix C.

Air entered the tube axially through a section made of stainless steel tubing. This section served to remove any swirl motion from the air stream before it entered the water injection section. The calming section was approximately 2-1/2 ft long and was fitted with straightening vanes at each end.

The water injection section was 6 in. long and was located just above the inlet calming section. It consisted of a porous bronze tube inserted into a Plexiglas body which was machined to provide an annular pressure chamber. A photograph of this section is shown in Figure 3.3. Water was directed tangentially into the pressure chamber from opposite directions and forced into the tube through the bronze. This method of injection was used because it introduced the water evenly over a relatively large area at low velocity. Thus, the water did not tend to separate from the wall as it entered; and essentially all of it flowed initially as a film along the wall.

In order to make it possible to carry out experimental measurements at various positions downstream of the water injection section, the rest of the tube was made of seven interchangeable sections having various lengths. One of these sections was designed so that the water film could be removed through another porous bronze tube. This made it possible to measure the dispersed water fraction as described in Section 3.3 below. The design of the film removal

FIGURE 3.2
SECTIONS OF THE TEST SECTION

FIGURE 3.3
WATER INJECTION SECTION

section was similar to that of the water injection section. A photograph of the film removal section is shown in Figure 3.4.

Three of the remaining six sections were machined from Plexiglas and could be used to visually observe or photograph the flow. One of these sections is shown in Figure 3.5.

The Plexiglas sections and the film removal section were each 6 in. long. The remaining three sections were made of stainless steel tubing. Their lengths were approximate multiples of 6 in. which were chosen so that either the film removal section or a Plexiglas section could be located at any one of twenty-two 6 in. intervals above the water injection section.

Except for the inlet and exit sections, each section of the test section had a male flange on one end and a female flange on the other. The design of these flanges was such as to avoid any significant discontinuities at the various joints while providing for an adequate seal. The entire test section was supported by an aluminum channel bolted to the floor and ceiling of the experimental room. The test section was clamped to this channel and vertically aligned by means of adjustable clamps. Hydraulic connections to the inlet and exit sections and to the injection and removal sections were by means of flexible tubing.

4. Apparatus for measuring inlet pressure and pressure drop.- The static pressure at the tap located near the top of the water injection section was measured by means of a Bourdon gage. The pressure drop between this tap and a similar tap located near the top of the film removal section was measured by means of a U tube

FIGURE 3.4
FILM REMOVAL SECTION

DIRECTION OF FLOW

FIGURE 3.5
PLEXIGLAS SECTION

manometer. A larger, well-type manometer was also available. In order to assure that only one phase was present in the tubing connecting the gage and manometer to the test section, a slight gas purge was maintained through the pressure taps. In addition, check valves were located at each of the taps. The purge gas was compressed nitrogen supplied from a bottle equipped with a pressure regulating valve. A pair of identical rotameters was provided to establish a visual check on the purge rates. The purge rates could be adjusted by means of needle valves located at the exit of each rotameter. Valves were also provided which could be used to equalize the pressure on the two legs of the manometer or to isolate it from the hydraulic system. Finally, traps were provided for collecting condensation or fluid accidentally forced from the manometer.

5. Apparatus for air-water separation and water collection.-

The mixture of air and water leaving the top of the test section passed through two cyclone separators arranged in parallel. Air leaving the separators could be directed to the atmosphere through either or both of the throttling valves used to control the air flow rate. Water leaving the separators could be directed either to a 60 gallon storage tank or to a small collection tank. The collection tank had a capacity of approximately 2 gallons and was provided with a calibrated sight glass for use in measuring the water collection rate. Tank selection could be made by properly positioning two manually-operated, quick-acting ball valves.

When the dispersed water fraction was being determined as described in Section 3.3.2 below, a mixture of air and water also

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flowed from the test section through the wall of the porous bronze cylinder in the film removal section. This mixture was separated and the water collected by means of apparatus similar to but separate from that described above. (When the dispersed water fraction was not being determined, a gate valve was used to isolate this apparatus from the test section.) The mixture from the film removal section was directed to another pair of cyclone separators arranged in parallel. The air leaving these separators flowed first through a rotameter and then to the atmosphere through a needle valve which could be used to control the rate at which air was bled from the system. The pressure and temperature of air leaving the rotameter were measured respectively by means of a Bourdon gage and a thermocouple. These measurements could be used in combination with the rotameter reading to determine the air bleed rate. Water leaving the separators could be directed either to a 60 gallon storage tank or to one of two small collection tanks. The collection tanks had approximate capacities of 2 and 0.2 gallons and were each provided with a calibrated sight glass for use in measuring the water collection rate. Tank selection could be made by properly positioning three manually-operated, quick-acting ball valves.

Miscellaneous valves and pipes were provided which made it possible to move water from the collection tanks to the storage tanks and from the storage tanks back to the supply tank using one or the other of the two sources of compressed air mentioned above. In addition, tubing and valves were provided which allowed the necessary venting and equalization of pressure as water was collected or moved from place to place.

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6. Valve and instrumentation panels.-- To facilitate operation of the hydraulic system, most of the valves and the instrumentation were mounted on one of three plywood panels as shown in Figure 3.6. Valves and instrumentation related to the air supply apparatus, valves and instrumentation related to the apparatus used to measure inlet pressure and pressure drop and instrumentation for reading the thermocouples were located on the left panel. A window for viewing the test section, valves and instrumentation related to the water supply apparatus, valves and instrumentation related to the apparatus for air-water separation and water collection, and valves used to regulate the rate of air flow through the test section were located on the center and right panels.

3.2.2 Motion Picture Equipment

The equipment used to obtain motion pictures of the disturbance waves on the surface of the water film was arranged as shown in Figure 3.7. The camera was driven by a universal motor and was designed for continuous motion of the film at speeds up to 3000 frames/sec. It was supported on a stand which minimized vibration during filming and permitted adjustment of its vertical position. Three 50,000 candle power flood lamps were held in a special fixture which was attached to a tripod permitting adjustment of their vertical position and angle of tilt. The camera was focused on one of the Plexiglas sections of the test section. A timer was constructed which consisted of a pointer rotated in front of a marked disc by a universal motor. Part of a meter stick was used as a scale. The timer and scale were mounted adjacent to the Plexiglas section.

LEFT SIDE PANEL

- (1) Nitrogen cylinders
- (2) Manometer indicating orifice pressure drop
- (3) Potentiometer and rotary switches
- (4) Rotameter indicating nitrogen purge flow rate
- (5) Pressure gage indicating orifice inlet pressure
- (6) Pressure regulating valve to control test section inlet pressure
- (7) Pressure gage indicating test section inlet pressure
- (8) Manometer indicating test section pressure drop

MIDDLE PANEL

- (9) Test section
- (10) Rotameter indicating water flow rate
- (11) Globe control water flow valve
- (12) Sight glass connected to water tanks
- (13) Valve separation and union apparatus
- (14) Pressure indicating air pressure supply tank

RIGHT SIDE PANEL

- (15) Rotameter indicating air bleed rate from water collection apparatus
- (16) Pressure gage indicating pressure at inlet to bleed rotameter
- (17) Valves to regulate air bleed rate from water collection apparatus
- (18) Valves to regulate air flow rate through test section

3.6 VALVE AND INSTRUMENTATION PANELS

FIGURE 3.7
MOTION PICTURE EQUIPMENT

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Black felt was used as a background material. The timer speed was controlled by means of a Variac which regulated the voltage applied to the motor. Timer speed was measured using a stroboscope.

The projector used to analyze the motion picture films was a Time and Motion Study Projector. This projector was designed so that the films could be analyzed at slow speed or one frame at a time.

3.3 Experimental Procedures

A detailed outline of the experimental procedures is given in Appendix D. The following discussion is a brief description of these procedures.

3.3.1 General Procedure

In order to carry out experimental measurements of the dispersed water fraction or pressure drop at a particular position downstream of the water injection section, the sections of the test section were arranged to locate the film removal section at this position. Similarly, to obtain motion pictures of the disturbance waves at a particular position, the test section was arranged to locate one of the Plexiglas sections at this position.

A particular flow condition was established by setting the air mass flow rate, water mass flow rate, and the pressure and temperature at the test section inlet. The air mass flow rate was varied from 51 to 251 lb/hr. The water mass flow rate was varied from 102 to 524 lb/hr. The inlet pressure was varied from 40 to 90 psia. The temperatures of the air and water at the test section inlet were kept constant at approximately 70°F. The particular combinations of air and water mass flow rates and inlet pressures which were used are

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given in Tables F.1 and F.2 of Appendix F. These flow conditions are compared with the annular to semiannular flow regime transition in Figure B.2 of Appendix B.

For each of the flow conditions listed in Tables F.1 and F.2, the dispersed water fraction and total pressure drop were determined at from 7 to 9 different positions extending to approximately 11 ft downstream of the water injection section. Motion pictures of the disturbance waves were taken for seven of these conditions at 3 different positions extending to approximately 10 ft downstream of the water injection section. The particular flow conditions for which motion pictures were taken are given in Table F.3 of Appendix F.

3.3.2 Procedure Used to Measure Dispersed Water Fraction and Pressure Drop

For a particular experimental condition, the dispersed water fraction at the location of the film removal section was determined from measurements of the film and dispersed water mass flow rates.

The film mass flow rate was measured by removing the film through the porous bronze wall using the differential pressure between the test section and the atmosphere. The water removed through the bronze was separated from the air removed along with it by means of the pair of cyclone separators mentioned in Section 3.2.1. Water from these separators was continuously drained into a collection tank and the rate of collection determined by observing the change in the tank during a time interval measured with a stop watch.

The dispersed water which was not removed through the porous wall was separated from the air leaving the test section exit by means

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of another pair of cyclone separators. Water from these separators was continuously drained into another collection tank. The rate of collection in this tank was also determined by observing the change in water level during a measured time interval.

In order to check that the film was being completely removed, the above procedure was repeated for several values of the rate of air removal through the porous wall. The rate of air removal was varied by regulating the air bleed rate from the air-water separation and water collection apparatus. When the bleed rate was such that the ratio of the dispersed water collection rate to the total collection rate was essentially independent of the rate of air removal, it was assumed that the film was being completely removed and that this ratio was equivalent to the dispersed water fraction. Typical results obtained using this technique are shown in Figure 3.8.

The assumption that the film was being completely removed could be checked by visual inspection of the transparent tube as shown in Figure 3.9.

The pressure drop between the water injection section and the film removal section was measured by means of the nitrogen-purged manometer system described in Section 3.2.1. When making this measurement, the nitrogen purge rates to the two pressure taps were adjusted so that they were equal. The magnitude of these purge rates was always negligible compared to the air flow rate through the test section.

3.3.3 Procedure Used to Make Visual Observations with a Stroboscope

For each experimental condition, a stroboscope was used to visually observe the water film. This observation was made by

$D = 0.497$ in.
 $t_l = 70^\circ\text{F}$
 $P_l = 90$ psia
 $W_L = 102$ lb/hr
 $Z = 130.25$ in.

$\circ$ $W_G = 51$ lb/hr
 $\square$ $W_G = 101$ lb/hr
 $\diamond$ $W_G = 151$ lb/hr
 Δ $W_G = 201$ lb/hr
 $\circ$ $W_G = 251$ lb/hr

FIGURE 3.8

EFFECT OF AIR REMOVAL RATE ON THE RATIO OF THE DISPERSED WATER COLLECTION RATE TO THE TOTAL COLLECTION RATE

FIGURE 3.9

PHOTOGRAPH OF THE FILM REMOVAL SECTION
DURING MEASUREMENT OF THE DISPERSED
WATER FRACTION

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directing the stroboscope at the Plexiglas section immediately downstream of the water injection section. The flash frequency was adjusted until it could be observed whether or not disturbance waves were present on the film surface at this location. This determination could be made by adjusting the flash frequency until it was approximately equal to the average frequency of appearance of the waves. When this was the case the waves could be easily observed.

3.3.4 Procedure Used to Obtain and Analyze the Motion Pictures Films

In order to obtain motion pictures of the disturbance waves for a particular flow condition, the camera was focused on one of the Plexiglas sections of the test section. The timer and scale described in Section 3.2.2 were also included in the picture. Once the flow condition was established, the timer was started and its speed measured with the stroboscope. Then the camera was started and the motion pictures were taken.

After development, the motion picture films were analyzed at slow speed and one frame at a time by projecting them onto an 18 in. by 24 in. white card. This card was marked with evenly spaced horizontal lines and mounted on a standard projection screen. The distance between the projector and the screen was adjusted so that the spacing of the horizontal lines was equivalent to 1/8 in. according to the scale mounted next to the test section.

For a particular roll of film, wave frequency was measured by counting the number of waves which passed the center of the Plexiglas section during a time interval measured by means of the timer mounted next to the test section. The individual velocity of a

particular wave was determined by measuring the distance traveled by the wave during a time interval which was again determined from the timer mounted next to the test section. The time interval for the velocity measurement was chosen so that the distance traveled by the wave was from 1 to 3 in. The distance measurement was made by noting the initial and final positions of the wave relative to the horizontal lines on the white card. These lines were also used to measure the disturbance length of a particular wave at a position near the center of the Plexiglas section.

3.4 Data Reduction

In order to reduce the experimental data, two Fortran programs were written for the IBM 7094 computer. One was used to reduce the data obtained from measurements of the dispersed water fraction and pressure drop. The other was used to reduce data obtained from the motion pictures. A detailed description and flow diagram of each of these programs is given in Sections E.1 and E.2 of Appendix E.

CHAPTER IV

EXPERIMENTAL RESULTS

4.1 Results of Measurements of the Dispersed Water Fraction

The results of measurements of the dispersed water fraction are tabulated in Table F.1 of Appendix F. This table shows that measured values of this quantity ranged from 0.003 to 0.453.

A cross section of these results which shows the effects of each of the independent variables is presented graphically in Figures 4.1, 4.2 and 4.3. From these figures, it can be observed that, for a particular flow condition, the dispersed water fraction increases continuously with distance downstream of the water injection section. The rate of increase with distance initially decreases along the tube. However, at distances greater than 60 in. from the water injection section, the rate of increase with distance becomes approximately constant and the dispersed water fraction increases almost linearly along the tube.

Figure 4.1 shows that, for a constant water mass flow rate and inlet pressure, the rate of increase of the dispersed water fraction with distance at a particular position downstream of the water injection section increases with an increase in air mass flow rate. As a result, the dispersed water fraction at a particular position along the tube also increases with an increase in air mass flow rate.

Figure 4.2 shows that, for constant air and water mass flow rates, the rate of increase of the dispersed water fraction with distance at a particular position downstream of the water injection section increases with a decrease in inlet pressure. Thus, the

FIGURE 4.1

EFFECT OF AIR MASS FLOW RATE ON THE DISPERSED WATER FRACTION

FIGURE 4.2
EFFECT OF INLET PRESSURE ON THE DISPERSED WATER FRACTION

FIGURE 4.3

EFFECT OF WATER MASS FLOW RATE ON THE DISPERSED WATER FRACTION

dispersed water fraction at a given position along the tube also increases with a decrease in pressure.

Finally, Figure 4.3 shows that, for a constant air mass flow rate and inlet pressure, the rate of increase of the dispersed water fraction with distance at a particular position downstream of the water injection section does not vary significantly with water mass flow rate. As a result, the dispersed water fraction at a particular position along the tube is approximately independent of water mass flow rate.

4.2 Results of Measurements of Pressure Drop

Results of measurements of the pressure drop between the water injection section and the film removal section are tabulated in Table F.2 of Appendix F. This table shows that the pressure drop between the water injection section and the largest distance along the tube for which measurements of this quantity were made ranged from 1.40 to 15.81 psi. The corresponding range of values of the ratio of pressure drop to the inlet pressure was 0.016 to 0.20.

A cross section of these results which shows the effect of the independent variables is presented graphically in Figures 4.4, 4.5 and 4.6. From these figures, it can be observed that, for a particular experimental condition, the pressure drop increases almost linearly along the tube at distances greater than approximately 30 in. from the water injection section. In other words, the pressure gradient is approximately constant at distances greater than 30 in. from the water injection section. At distances less than this the pressure gradient is somewhat higher.

FIGURE 4.4
EFFECT OF AIR MASS FLOW RATE ON PRESSURE DROP

FIGURE 4.5
EFFECT OF INLET PRESSURE ON PRESSURE DROP

FIGURE 4.6
EFFECT OF WATER MASS FLOW RATE ON PRESSURE DROP

Figure 4.4 shows that, for a constant water mass flow rate and inlet pressure, the pressure gradient increases with an increase in air mass flow rate. Figure 4.5 shows that, for constant air and water mass flow rates, the pressure gradient increases with a decrease in inlet pressure. Finally, Figure 4.6 shows that, for a constant air mass flow rate and inlet pressure, the pressure gradient increases with an increase in water mass flow rate.

4.3 Observations of the Disturbance Waves with a Stroboscope

Visual observations of the disturbance waves on the surface of the water film using a stroboscope showed that these waves were present immediately downstream of the porous bronze cylinder in the water injection section for each of the flow conditions which were studied. Since the separation time between waves was not constant for a particular flow condition, it was not possible to synchronize the flash frequency of the stroboscope with the frequency of appearance of the waves. As a result, quantitative measurements of such variables as wave frequency, velocity and disturbance length could not be made using this technique.

4.4 Results Obtained from the Motion Pictures

In the motion pictures, the disturbance waves appear as irregularly spaced areas of disturbed liquid moving along the film surface. They are therefore to be contrasted with regularly spaced, sinusoidal ripples. The disturbed area of a particular wave has a "milky" appearance which probably is a result of light scattering from the ruffled surface. Thus these waves are easily observed.

Three frames from the motion picture films have been

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enlarged and are shown in Figures 4.7, 4.8 and 4.9. These frames all correspond to the same flow condition. However, each one was obtained at a different distance from the water injection section. Figures 4.7, 4.8 and 4.9 show that the disturbance waves could be easily observed at each of the three locations. The increase in the amount of dispersed water along the tube can also be observed in these figures.

Values of disturbance wave frequency, average velocity and average disturbance length obtained from analysis of the motion picture films are tabulated in Table F.3 of Appendix F. As an indication of the dispersion of individual values of these quantities from their average value for a particular flow condition, values of the standard deviation are also given in Table F.3.

From Table F.3 it can be observed that the number of waves measured for a given flow condition ranged from 41 to 263. This table also shows that measured values of the wave frequency ranged from 36.8 to 149.7 waves/sec. Values of the average wave velocity ranged from 11.9 to 23.9 ft/sec. The corresponding range of superficial air velocity was 45.8 to 135 ft/sec. Values of the average disturbance length ranged from 0.277 to 0.506 in.

4.4.1 Results of Measurements of Wave Frequency

Figures 4.10, 4.11, and 4.12 show the effect of the independent variables on wave frequency. From these figures, it can be observed that, for a particular experimental condition, the frequency decreases along the tube. However, at distances greater than 60 in. downstream of the water injection section, the rate of decrease is

FIGURE 4.7
TYPICAL FRAME FROM MOTION PICTURE FILMS

FIGURE 4.8

TYPICAL FRAME FROM MOTION PICTURE FILMS

FIGURE 4.9
TYPICAL FRAME FROM MOTION PICTURE FILMS

FIGURE 4.10
EFFECT OF AIR MASS FLOW RATE ON WAVE FREQUENCY

FIGURE 4.11
EFFECT OF INLET PRESSURE ON WAVE FREQUENCY

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FIGURE 4.12

EFFECT OF WATER MASS FLOW RATE ON WAVE FREQUENCY

small and the frequency becomes approximately constant. The motion pictures show that the decrease in frequency along the tube is caused by wave agglomeration. This process results from the fact that all disturbance waves do not have the same velocity. Thus the faster waves tend to overtake the slower ones. Since wave agglomeration depends upon differences between the wave velocities, it continues to take place at large distances from the inlet. However, the results shown in Figures 4.10, 4.11 and 4.12 indicate that this process is only of importance within the first 60 in. downstream of the water injection section.

Figure 4.10 shows that, for a constant water mass flow rate and inlet pressure, the wave frequency at a particular position downstream of the water injection section increases with air mass flow rate. Figure 4.11 shows that, for a constant air and water mass flow rate, the wave frequency at a particular downstream position increases with a decrease in inlet pressure. Figure 4.12 shows that, for a constant air mass flow rate and inlet pressure, the wave frequency at a particular position downstream of the water injection section increases to some extent with water mass flow rate; however, this effect is relatively small.

4.4.2 Results of Measurements of Wave Velocity

Figures 4.13, 4.14 and 4.15 show the effect of the independent variables on average wave velocity. These figures show that, for a particular experimental condition, the average wave velocity increases gradually along the tube. However, at a distance of 12.75 in. downstream of the water injection section, the average wave

FIGURE 4.13

EFFECT OF AIR MASS FLOW RATE ON AVERAGE WAVE VELOCITY

FIGURE 4.14
EFFECT OF INLET PRESSURE ON AVERAGE WAVE VELOCITY

FIGURE 4.15

EFFECT OF WATER MASS FLOW RATE ON AVERAGE WAVE VELOCITY

velocity is only slightly less than the average wave velocity at 125.25 in. For the experimental conditions which were observed, disturbance waves are therefore accelerated within a very short distance downstream of the water injection section.

Figure 4.13 shows that, for a constant water mass flow rate and inlet pressure, average wave velocity increases with air mass flow rate. Figure 4.14 shows that, for constant air and water mass flow rates, the average velocity also increases with a decrease in inlet pressure. Figure 4.15 shows that, for constant air mass flow rate and inlet pressure, the average wave velocity increases with an increase in water mass flow rate; however, this effect is relatively small.

Individual wave velocities are distributed about the average value for a particular experimental condition. Typical histograms are shown in Figure 4.16. This figure shows the depletion of lower velocity waves with distance along the tube which results from the agglomeration process. This effect does not cause a significant change in the standard deviation of the wave velocity distribution however.

4.4.3 Results of Measurements of Wave Disturbance Length

Figures 4.17, 4.18 and 4.19 show the effect of the independent variables on the average wave disturbance length. From these figures, it can be observed that, for a particular experimental condition, the average disturbance length decreases slightly along the tube for most of the experimental conditions observed.

Figure 4.17 shows that, for a constant water mass flow rate

$D = 0.497 \text{ in.}$
 $t_1 = 70^\circ\text{F}$
 $P_1 = 90 \text{ psia}$
 $W_G = 201 \text{ lb/hr.}$
 $W_L = 411 \text{ lb/hr.}$

FIGURE 4.16

TYPICAL HISTOGRAMS OF WAVE VELOCITY MEASUREMENTS

FIGURE 4.17

EFFECT OF AIR MASS FLOW RATE ON AVERAGE WAVE DISTURBANCE LENGTH

FIGURE 4.18
EFFECT OF INLET PRESSURE ON AVERAGE WAVE
DISTURBANCE LENGTH

FIGURE 4.19
EFFECT OF WATER MASS FLOW RATE ON AVERAGE WAVE
DISTURBANCE LENGTH

and inlet pressure, the average disturbance length does not vary with air mass flow rate in any clearly definable way. However, Figure 4.18 shows that, for constant air and water mass flow rates, the average disturbance length decreases slightly with a decrease in pressure. Figure 4.19 shows that, for constant air mass flow rate and inlet pressure, the average disturbance length increases with water mass flow rate.

As in the case of wave velocity, individual wave disturbance lengths are distributed about the average value for a particular experimental condition. Histograms of typical distributions are presented in Figure 4.20.

4.5 Accuracy and Reproducibility

The accuracy and reproducibility of the experimental measurements is discussed in considerable detail in Appendix G. The principal conclusions reached in this discussion are outlined briefly below.

The uncertainty of a particular measurement of air mass flow rate probably ranged from 1.4 per cent for the highest air flow rate used to 2.5 per cent for the lowest. The uncertainty of a particular measurement of water mass flow rate was probably less than 2 per cent. Particular values of either of these variables could be reproduced to within 1 per cent.

Both the uncertainty and extent of reproducibility of values of the absolute pressure at the test section inlet were probably within the range from 0.5 to 1.25 per cent. The average air and water temperature at the test section inlet was always within 1°F of 70°F.

$D = 0.497$ in.
 $t_f = 70^\circ F$
 $P_f = 90$ psia
 $W_G = 201$ lb/hr.
 $W_L = 411$ lb/hr.

FIGURE 4.20

Because of the slight effect of air removal rate on the measurement of dispersed water fraction, a particular value of this quantity probably has an absolute uncertainty of from 0.001 to 0.005. In addition, the uncertainty resulting from the measurement of the water collection rates could be as much as 3 per cent. Thus, a dispersed water fraction of 0.05 could have a total uncertainty of from 5 to 13 per cent. On the other hand, the uncertainty of a dispersed water fraction of 0.500 should be 4 per cent or less. Measurements of the dispersed water fraction which were repeated for several flow conditions were always found to be reproducible within these limits.

The uncertainty of measurements of pressure drop probably ranged from approximately 35 per cent for the lowest values of this quantity to about 0.3 per cent for the highest values. Measurements of pressure drop which were repeated for a particular flow condition were always found to be within 1.5 to 2 per cent of previously measured values.

The experimental uncertainty of a particular measurement of wave frequency was probably about 1 per cent. However, measurements of this quantity made from two different rolls of film for a particular flow condition were only consistent to within 1.4 to 7.5 per cent. The fact that reproducibility is not as good as would be expected from the experimental uncertainty is probably because the experimental uncertainty does not take into account the statistical nature of this quantity. This is supported by the fact that values of the standard deviation calculated as described in Appendix E, Section E.2

were from 8 to 16 per cent of the corresponding value of wave frequency.

The experimental uncertainty of individual measurements of wave velocity was probably from 6 to 12 per cent. However, the principal contribution to this uncertainty is from errors of observation which, for a large number of measurements, should tend to average out. As a result, the uncertainty of the average wave velocity for a particular flow condition is probably less. This is supported by the fact that values of average wave velocity determined from different rolls of film for a particular flow condition were consistent within from 0.5 to 5.4 per cent.

The uncertainty of a particular measurement of wave disturbance length was probably about $1/16$ in. Therefore, since the disturbance length of individual waves varied from $1-1/4$ in. to $1/8$ in., the corresponding uncertainty was probably from 5.5 to 50 per cent. However, as in the case of the wave velocity measurements, the uncertainty of the average wave disturbance length for a particular experimental condition was probably less than this. This is indicated by the fact that values of average disturbance length determined from different rolls of film for a particular flow condition were consistent within 1.3 to 26 per cent.

Finally, from Table F.3 of Appendix F, it can be seen that, for some flow conditions, the standard deviation of individual values of wave disturbance length or wave velocity about the average value is greater than would be expected from errors of observation alone. Therefore, the dispersion of individual values about the average value for a particular flow condition is probably statistical to some extent.

CHAPTER V

ANALYSIS AND CORRELATION OF THE EXPERIMENTAL RESULTS

The experimental results shown in Figures 4.1, 4.2, and 4.3 of Chapter IV show that, for a particular flow condition within the range used for the experiments described in this thesis, the dispersed water fraction continues to increase almost linearly along the tube at distances extending to 130.25 in. or 262 diameters downstream of the water injection section. The purpose of the following discussion is to consider the possible reasons for this result and, from this, to develop a semi-empirical correlation of the experimental values of the dispersed water fraction which are reported in this thesis.

5.1 Analysis of the Variation of the Dispersed Water Fraction along the Tube

The qualitative observations made with a stroboscope showed that disturbance waves were present immediately downstream of the porous bronze cylinder in the water injection section for each of the flow conditions which were studied. As mentioned in Chapter II, high speed motion pictures of disturbance waves in annular, air-water flow obtained by Hall-Taylor and Hewitt (15) have indicated that the action of the air on these waves might be the cause of entrainment of water from the film. The motion pictures which were obtained during the present study fully support this observation. Streams of water droplets were frequently seen being transported from the crests of the disturbance waves and dispersed into the air. On the other hand, the surface of the film between the disturbance waves was relatively quiescent and did not appear to be directly involved in the process.

On the basis of these observations, it seems probable that the increase of the dispersed water fraction immediately downstream of the water injection section is due to the formation of disturbance waves and the subsequent entrainment of water from their crests by the air. However, as the concentration of dispersed water increases along the tube, deposition of droplets by turbulent eddy transport should also become significant. Thus, at a given location downstream of the water injection section, it should be possible to express the rate of increase of the mass flow rate of dispersed water along the tube as follows:

$$\frac{dW_d}{dz} = E - \Delta \quad (5-1)$$

where E is the rate of entrainment ($\text{lb}_m/\text{hr ft}$) and Δ is the rate of deposition ($\text{lb}_m/\text{hr ft}$).

Since eddy transport of small water droplets in a turbulent air stream is probably similar to other turbulent flow transport processes, it should be more or less random and statistical in nature. Therefore, it should be possible to express the rate of deposition in terms of a mass transport coefficient, K (ft^2/hr), and the average concentration of dispersed water in the air, C (lb_m/ft^3), by an equation such as the following:

$$\Delta = K C \quad (5-2)$$

The average concentration of dispersed water in the air is related to the mass flow rate, W_d , by the expression:

$$W_d = \frac{C V_G A_c}{\gamma} \quad (5-3)$$

where V_G is the average air velocity (ft/hr), A_c is the cross

sectional area of the dispersed phase (ft^2), and γ is the ratio of the average air velocity to the average velocity of the water droplets. Since $W_G = \rho_G V_G A_c$ where ρ_G is the air density (lb_m/ft^3), Equation (5-3) can also be written as follows:

$$W_d = C \frac{W_G}{\rho_G \gamma} \quad (5-4)$$

Thus, using Equation (5-1) and (5-4), one can write the following differential equation for the rate of increase of the mass flow rate of dispersed water with position downstream of the water injection section:

$$\frac{dW_d}{dz} = E - \frac{K\gamma}{W_G/\rho_G} W_d \quad (5-5)$$

For steady adiabatic flow, the mass flow rate of the air, W_G , is constant. However, the air density, ρ_G , (and therefore the ratio, W_G/ρ_G) decreases with distance from the inlet as a result of the pressure gradient. The velocity ratio, γ , should be a function of: (1) the air velocity distribution and (2) the size distribution of the water droplets. The rate of entrainment, E , probably depends upon: (1) the shear stress at the film surface, (2) the average velocity of the air relative to that of the film, (3) surface conditions of the film, and (4) tube diameter. Finally, the droplet transport coefficient, K , is probably a function of: (1) the average velocity and velocity distribution of the dispersed phase, (2) the size distribution of the liquid droplets, and (3) the diameter of the core of the tube occupied by the dispersed phase (or, alternatively, the film thickness and tube diameter).

For the experiments described in this thesis, the tube diameter was fixed; and, for a particular flow condition, the mass flow rates of air and water, the inlet pressure, and the inlet temperature were constant. Furthermore, for each of the flow conditions which were studied, the pressure gradient was approximately constant at distances greater than 30 in. or 60 diameters downstream of the water injection section; and quantities such as the frequency, mean velocity and mean length of the disturbance waves were approximately constant at distances greater than 60 in. or 120 diameters downstream of the water injection section. In addition, the magnitude of the pressure gradient was such that the rate of decrease in pressure along the tube was never greater than 1.8 per cent of the absolute pressure at the inlet per foot. Therefore, for the flow conditions which were studied, variables such as: (1) the average velocity and velocity distribution of the dispersed phase, (2) the average velocity and surface conditions of the water film, (3) the film thickness, and (4) the size distribution of water droplets probably did not change significantly along the tube at distances greater than 120 diameters from the water injection section. Under these circumstances, W_G/ρ_G , γ , E , and K should be approximately constant and, according to Equation (5-5), $\frac{dW_d}{dz}$ should decrease to zero as W_d increases along the tube.

The experimental observation that $\frac{dW_d}{dz}$ does not decrease to zero as predicted by Equation (5-5) appears to have two possible explanations:

- 1) The rate of deposition is small compared to the rate of

entrainment for the range of flow conditions which were studied.

- 2) At large distances from the water injection section, the rate of deposition is proportional to, but less than, the rate of entrainment.

Each of these possibilities is considered in the analysis which follows.

5.2 Derivation of an Expression for the Rate of Entrainment

The nature of the entrainment process as observed in the motion pictures suggests that the rate of entrainment should be proportional to the rate of energy transfer from the dispersed phase to the part of the film surface covered by disturbance waves. This relationship is expressed mathematically as follows:

$$E = B_0 \tau_i \pi D_c (V_c - V_f) N_w \quad (5-6)$$

where B_0 is a constant of proportionality, τ_i is the interfacial shear stress (lb_f/ft^2), D_c is the diameter of the core of the tube occupied by the dispersed phase (ft), $(V_c - V_f)$ is the difference between the average velocity of the dispersed phase and the average film velocity (ft/hr), and N_w is the average fraction of the film surface covered by disturbance waves (ft^2 of disturbance area/ ft^2 of film surface). The product, $\tau_i (V_c - V_f)$ is the net rate of energy transfer from the dispersed phase per unit area of the film surface.

The interfacial shear stress can be related to the total pressure gradient by applying the momentum equation to the control volume shown in Figure 5.1. The resulting expression is:

FIGURE 5.1

CONTROL VOLUME USED IN THE DERIVATION
OF EQUATION (5-7)

$$\begin{aligned}
 - dP \frac{\pi D_c^2}{4} - \tau_i \pi D_c dz - \rho_c \frac{g}{g_c} \frac{\pi D_c^2}{4} dz = \\
 \frac{1}{g_c} d(W_G V_G) + \frac{1}{g_c} d(W_d V_d)
 \end{aligned}
 \tag{5-7}$$

which, by rearranging, becomes

$$\begin{aligned}
 \tau_i = - \frac{dP}{dz} \frac{D_c}{4} - \rho_c \frac{g}{g_c} \frac{D_c}{4} - \frac{1}{\pi D_c g_c} \frac{d(W_G V_G)}{dz} \\
 - \frac{1}{\pi D_c g_c} \frac{d(W_d V_d)}{dz}
 \end{aligned}
 \tag{5-8}$$

The gravitational and acceleration terms in Equation (5-8) are usually small compared to the total pressure gradient. Therefore, to a first approximation, it should be possible to write this equation as follows:

$$\tau_i \approx \frac{1}{B_1} \left| \frac{dP}{dz} \right| \frac{D_c}{4}
 \tag{5-9}$$

where B_1 is a quantity which is slightly greater than unity and approximately constant.¹

In annular flow, the average velocity of the liquid film is usually small compared with the average velocity of the dispersed phase. In addition, the average velocity of the dispersed phase is approximately equivalent to the average velocity of the gas. Therefore, to a first approximation, it should be possible to express the difference between the average velocity of the dispersed phase and the

¹This assumption has been checked analytically using the computer program described in Appendix E, Section E.3. The results are discussed in Appendix H.

average film velocity as follows:

$$(V_c - V_f) \simeq \frac{1}{B_2} V_G \quad (5-10)$$

where B_2 is another quantity which is slightly greater than unity and approximately constant.² Then, since

$$V_G = \frac{W_G}{\rho_G \frac{\pi D_c^2}{4}} \quad (5-11)$$

and, according to the perfect gas law,

$$\rho_G = \frac{P}{RT} \quad (5-12)$$

$(V_c - V_f)$ can be expressed in terms of the air mass flow rate, pressure, and temperature as follows:

$$(V_c - V_f) \simeq \frac{1}{B_2} RT \frac{W_G}{P \frac{\pi D_c^2}{4}} \quad (5-13)$$

Hall-Taylor and Hewitt (15) observed that the disturbance waves in annular flow almost always symmetrical around the circumference of the tube. Therefore, to a good approximation, it should be possible to express the average fraction of the film surface covered by these waves in terms of frequency, mean velocity and mean disturbance length as follows:

$$N_W \simeq \frac{FL}{V_W} \quad (5-14)$$

²Ibid

The proportionality constant in Equation (5-6), B_0 , has the dimensions, $\text{lb}_m/\text{ft lb}_f$. Thus, it can be interpreted as the lb_m of water entrained per ft lb_f of energy transferred to the film surface. In general, this quantity is probably a function of the liquid surface tension. In particular, it would be expected to be inversely related to this property. However, for an air-water system at fixed temperature, B_0 should be approximately constant.

Finally, by substituting Equations (5-9), (5-13), and (5-14) into Equation (5-6) and cancelling terms where possible, the following equation is obtained for the rate of entrainment:

$$E = B_3 \left| \frac{dP}{dz} \right| \frac{W_G}{P} \left(\frac{FL}{V_W} \right) \quad (5-15)$$

where B_3 is a constant defined by the following equation:

$$B_3 = B_0 RT/B_1 B_2 \quad (5-16)$$

On the basis of the discussion given in Section 5.1, it might be possible to use this expression to interpret and correlate the results of measurements of the dispersed water fraction. However, before this can be done, it is necessary to utilize the results of measurements of the frequency, velocity and length of the disturbance waves to obtain information about the quantity, $\left(\frac{FL}{V_W} \right)$.

5.3 Development of an Empirical Expression for $\left(\frac{FL}{V_W} \right)$

The values of the measurements of disturbance wave frequency, average velocity and average disturbance length given in Table F.3 of Appendix F were used to calculate corresponding values of $\left(\frac{FL}{V_W} \right)$. The results of this calculation are included in Table F.3

and are shown graphically in Figures 5.2, 5.3 and 5.4.

Table F.3 shows that the value of $\left(\frac{FL}{V_W}\right)$ varied from 0.081 to 0.249. In other words, for the flow conditions and distances from the water injection section for which values of wave frequency, velocity, and disturbance length were measured, the average percentage of the film surface covered by disturbance waves varied from 8.1 to 24.9 per cent.

Figure 5.2 shows that, for a constant water mass flow rate and inlet pressure, $\left(\frac{FL}{V_W}\right)$ does not vary appreciably with air mass flow rate. In addition, Figure 5.3 shows that, for constant air and water mass flow rates, $\left(\frac{FL}{V_W}\right)$ is approximately independent of the inlet pressure. However, Figure 5.4 shows that, for constant air mass flow rate and inlet pressure, $\left(\frac{FL}{V_W}\right)$ increases with water mass flow rate. Thus, for the range of flow conditions for which motion pictures were taken, the value of $\left(\frac{FL}{V_W}\right)$ at a particular distance downstream of the water injection section is primarily a function of water mass flow rate.

In order to obtain quantitative information about the dependence of $\left(\frac{FL}{V_W}\right)$ on water mass flow rate, these two quantities are plotted against each other on logarithmic graph paper in Figure 5.5. One of the two lines shown on this graph corresponds to the values of $\left(\frac{FL}{V_W}\right)$ calculated for a distance of 12.75 in. downstream of the water injection section. The other line corresponds to the average values of $\left(\frac{FL}{V_W}\right)$ calculated for distances of 71.75 and 125.25 in. downstream of the water injection section. In each case, the line is drawn through the values of $\left(\frac{FL}{V_W}\right)$ which correspond to the same air mass flow rate

FIGURE 5.2

EFFECT OF AIR MASS FLOW RATE ON (FL/V_w)

FIGURE 5.3
EFFECT OF INLET PRESSURE ON (F_L / V_w)

FIGURE 5.4
EFFECT OF WATER FLOW RATE ON (FL/V_w)

$D = 0.497$ in.

$t_1 = 70^\circ\text{F}$

NO. OF DATA POINTS = 21

SHADED SYMBOLS CORRESPOND TO $Z = 125.25$ in.

- $\triangle$ $P_1 = 40$ psia, $W_G = 101$ lb/hr, $W_L = 199$ lb/hr
- $\circ$ $P_1 = 90$ psia, $W_G = 101$ lb/hr, $W_L = 199$ lb/hr
- $\square$ $P_1 = 90$ psia, $W_G = 151$ lb/hr, $W_L = 299$ lb/hr
- $\diamond$ $P_1 = 90$ psia, $W_G = 201$ lb/hr, $W_L = 199$ lb/hr
- $\triangle$ $P_1 = 90$ psia, $W_G = 201$ lb/hr, $W_L = 299$ lb/hr
- $\square$ $P_1 = 90$ psia, $W_G = 201$ lb/hr, $W_L = 411$ lb/hr
- $\circ$ $P_1 = 90$ psia, $W_G = 251$ lb/hr, $W_L = 299$ lb/hr

FIGURE 5.5

LOGARITHMIC GRAPH SHOWING EFFECT
OF WATER MASS FLOW RATE ON $\left(\frac{FL}{V_W}\right)$

5-15

and inlet pressure. The slopes of these lines are, respectively, 0.45 and 0.55. Therefore, to a first approximation, values of $\left(\frac{FL}{V_W}\right)$ at a particular distance downstream of the water injection section can be correlated by the following empirical equation:

$$\left(\frac{FL}{V_W}\right) = B_L(Z) W_L^{0.5} \quad (5-17)$$

where $B_L(Z)$ is a quantity which is a function of distance from the water injection section.

Values of $B_L(Z)$ were calculated for each of the values of $\left(\frac{FL}{V_W}\right)$ in Table F.3. The results are shown graphically in Figure 5.6. The solid line is drawn through the average value of $B_L(Z)$ at each of the three positions along the tube. It can be observed that the average value of $B_L(Z)$ decreases with distance from the water injection section. However, at distances greater than 60 in., the rate of decrease along the tube is small and the average value of $B_L(Z)$ is approximately constant. Since, for a particular flow condition, the average velocity and disturbance length of the waves are approximately independent of distance from the water injection section, the decrease of $B_L(Z)$ along the tube is primarily due to the corresponding decrease in wave frequency caused by the agglomeration process.

The dashed lines in Figure 5.6 indicate the range of values of $B_L(Z)$ within 12.5 per cent of the average value. It can be observed that 26 of the 27 values of $B_L(Z)$ shown on this graph are within this range. As discussed in Appendix H, this range is probably within the experimental uncertainty. However, to some extent, this range could also be the result of the fact that $B_L(Z)$ is not entirely independent of variables such as W_G and P_1 or that the

FIGURE 5.6

VARIATION OF $B_4(Z)$ WITH DISTANCE FROM THE WATER INJECTION SECTION

exponent of W_L in Equation (5-17) is not exactly 0.5.

5.4 Development of a Semi-empirical Expression for the Dispersed Water Fraction

Equations (5-15) and (5-17) can now be combined to give the following equation for E:

$$E = B_3 B_4(Z) \left| \frac{dP}{dZ} \right| \frac{W_G}{P} W_L^{0.5} \quad (5-18)$$

Substitution of this equation into Equation (5-1) then gives

$$\frac{dW_d}{dZ} = B_3 B_4(Z) \left| \frac{dP}{dZ} \right| \frac{W_G}{P} W_L^{0.5} - \Delta \quad (5-19)$$

As mentioned in Section 5.1, one possible explanation of the experimental observation that $\frac{dW_d}{dZ}$ does not decrease to zero at large distances from the water injection section is that the rate of deposition of dispersed water, Δ , might be small compared to the rate of entrainment. If this is the case, Equation (5-19) can be approximately written as follows:

$$\frac{dW_d}{dZ} = B_3 B_4(Z) \left| \frac{dP}{dZ} \right| \frac{W_G}{P} W_L^{0.5} \quad (5-20)$$

Rearranging this equation then gives the following expression:

$$\frac{\frac{dW_d}{dZ} P}{\left| \frac{dP}{dZ} \right| W_G W_L^{0.5}} = B_3 B_4(Z) \quad (5-21)$$

For a particular flow condition, values of $\frac{dW_d}{dZ}$, $\frac{dP}{dZ}$, and P can be calculated as a function of distance downstream of the water injection section using the experimental values of W_d and P given in Tables F.1 and F.2. From these calculated quantities, it is then possible to calculate corresponding values of the left side of Equation (5-21). This was done for each of the flow conditions for

which motion pictures were taken, using the computer program described in Appendix E, Section E.3. The results are shown in Figure 5.7.

The solid line in Figure 5.7 is drawn through the average value at each of the nine positions along the tube for which experimental results were obtained. It can be observed that the average value of the left side of Equation (5-21) decreases along the tube. However, at distances greater than 60 in. downstream of the water injection section, the rate of decrease of this quantity along the tube is small and it becomes approximately constant.

The dashed lines in Figure 5.7 indicate the range of values of the left side of Equation (5-21) which are within 30 per cent of the average value. It can be seen that, at short distances from the water injection section, individual values of this quantity are within 25 per cent of the average value. However, at distances greater than 60 in., the range of individual values of the left side of Equation (5-21) is approximately 35 per cent.³

According to Equation (5-21), the ratio of the expression on the left side to $B_4(Z)$ is equal to B_3 which is defined by Equation (5-16) in Section 5.2. Therefore, in accordance with the assumptions made in Section 5.2, this ratio should be approximately constant along the tube. However, Figure 5.8 shows that the ratio of the average value of the expression on the left side of Equation (5-21) to the average value of $B_4(Z)$ corresponding to the solid line in Figure 5.6 varies by at least a factor of three along the tube.

³The possible reasons for this uncertainty are discussed in Appendix H.

FIGURE 5.7

VARIATION OF THE LEFT MEMBER OF EQUATION (5-21) WITH
DISTANCE FROM THE WATER INJECTION SECTION

5-20

FIGURE 5.8
 VARIATION OF THE RATIO OF THE AVERAGE VALUE OF THE
 LEFT SIDE OF EQUATION (5-21) TO THE AVERAGE VALUE OF
 $B_4(z)$ WITH DISTANCE FROM THE WATER INJECTION SECTION

5-21

If the assumption that the rate of deposition is small compared to the rate of entrainment is correct, Figure 5.8 indicates that B_3 is not constant along the tube. However, although B_3 probably would vary with distance along the tube to some extent, there is no apparent reason why it would vary as much as indicated in Figure 5.8. Therefore, it seems reasonable to conclude that the assumption that the rate of deposition is small compared to the rate of entrainment was incorrect and that

$$\frac{\frac{dW_d}{dZ} P}{\left| \frac{dP}{dZ} \right| W_G W_L^{0.5}} \neq B_3 B_4(Z)$$

as assumed in Equation (5-21).

Whatever the explanation of the difficulty described above, Figure 5.7 shows that values of the expression on the left side of Equation (5-21) calculated for several different experimental conditions are approximately the same at a given distance from the inlet. Therefore, to a first approximation, it is still possible to express the rate of increase of the mass flow rate of dispersed water with distance along the tube as follows:

$$\frac{dW_d}{dZ} = B_5(Z) \left| \frac{dP}{dZ} \right| \frac{W_G}{P} W_L^{0.5} \quad (5-22)$$

In terms of this equation, Figure 5.7 can be considered to be a graph of values of $B_5(Z)$ as a function of distance from the water injection section. In addition, on the basis of the preceding analysis, it is believed that $B_5(Z)$ is a quantity which is associated with the net rate of water transport from the film. Therefore, $B_5(Z)$ probably

varies along the tube as a result of: (1) a decrease in the rate of entrainment due to a decrease in the average fraction of the film surface covered by disturbance waves and (2) an increase in the rate of deposition due to an increase in the concentration of dispersed water. The fact that $B_5(Z)$ becomes approximately constant at large distances from the water injection section indicates that the rate of deposition reaches an asymptotic value which is proportional to, but less than, the rate of entrainment and that both rates remain approximately constant along the tube.

From Figure 5.7, it appears that values of $B_5(Z)$ corresponding to a particular flow condition decrease exponentially along the tube. If, for a particular flow condition, the asymptotic value of $B_5(Z)$ is taken to be the value at $Z = 127.25$ in., this possibility can be checked by plotting on semi-logarithmic graph paper the difference between this value and other values of $B_5(Z)$ corresponding to this flow condition as a function of distance from the water injection section. This has been done, and the result is shown in Figure 5.9. Also shown are values of the difference between the average value of $B_5(Z)$ at a particular distance from the water injection section and the average value of $B_5(Z)$ at $Z = 127.25$ in.

The solid line on Figure 5.9 is drawn through values of the difference between the average value of $B_5(Z)$ at a particular distance along the tube and the average value at $Z = 127.25$ in. The dotted lines are drawn through individual values of the difference corresponding to the various flow conditions. The equation of the solid line corresponding to the average values of $B_5(Z)$ is:

FIGURE 5.9

VARIATION WITH DISTANCE FROM THE INLET OF THE DIFFERENCE BETWEEN $B_5(Z)$ AND ITS VALUE AT $Z = 127.25$ in.

$$B_5(Z) = 0.070 + 0.72e^{-Z/17.65} \quad (5-23)$$

From Figure 5.9 it can be seen that, for a particular flow condition, the value of the ordinate at $Z = 0$ varies from 0.72 by approximately 50 per cent. However, since each data point shown on Figure 5.9 was obtained by calculating the difference between two values of $B_5(Z)$, this uncertainty should not be considered to be indicative of the uncertainty of an individual value of $B_5(Z)$ calculated from Equation (5-23). Instead, since Equation (5-22) agrees almost exactly with the solid line drawn in Figure 5.7, the uncertainty of individual values of $B_5(Z)$ calculated from this equation should be within the range indicated by this figure. In other words, the uncertainty of a particular value of $B_5(Z)$ calculated from Equation (5-23) should range from 25 to 35 per cent, depending on the value of Z .

A comparison of the slopes of the various lines drawn in Figure 5.9 shows that, with one exception, the slope of the dotted lines corresponding to the various flow conditions does not vary significantly from the slope of the solid line. Therefore, the uncertainty of the constant, 17.65, in Equation (5-23) is probably small compared with the uncertainty of the other two constants in this equation.

Finally Equations (5-22) and (5-23) can be combined to give the following equation:

$$\frac{dW_d}{dZ} = \left| \frac{dP}{dZ} \right| \frac{1}{P} W_G W_L^{0.5} \left[0.070 + 0.72e^{-Z/17.65} \right] \quad (5-24)$$

This equation can be approximately integrated from $Z = 0$ to a distance

5-25

Z downstream of the water injection section by replacing $\left| \frac{dP}{dZ} \right| \frac{1}{P}$ by its average value over this distance and then integrating the terms in the bracket. When this is done and both sides of the resulting expression are divided by W_L , the following semi-empirical expression is obtained for the dispersed water fraction:

$$\frac{W_d}{W_L} = \frac{W_G}{W_L^{0.5}} \frac{|\ln P/P_1|}{Z} \left[0.070 Z + 12.8 (1 - e^{-Z/17.65}) \right] \quad (5-25)$$

5.5 Comparison of Equation (5-25) with Experimental Values of the Dispersed Water Fraction

Since the uncertainty of the expression in the bracket of Equation (5-24) varies from 25 per cent near the inlet to 35 per cent further downstream, the resulting uncertainty of the expression in the bracket of Equation (5-25) should be approximately the same. As discussed in Appendix H, this uncertainty is probably a result of the assumptions made in Section 5.2 and the uncertainty of the experimental results used in the derivation of these expressions. From the discussion in Appendix G, one can show that the uncertainty of the remaining part of the right side of Equation (5-25) should vary from 3 to 6 per cent as a result of the uncertainties of particular values of W_G , W_L , P , and P_1 . Therefore, the total uncertainty of a particular value of the dispersed water fraction calculated from Equation (5-25) could be from 28 to 41 per cent.

Equation (5-25) was used to calculate values of the dispersed water fraction for each of the flow conditions for which this quantity was measured. The computer program used to make these calculations is described in Appendix E, Section E.4. The results of

this calculation are compared with the corresponding experimental results in Figures 5.10 through 5.13. In each of these figures, the solid line indicates exact agreement. The dashed lines indicate the range of values of the ordinate within 30 per cent of this line.

Figure 5.10 shows the comparison of the calculated and measured values of the dispersed water fraction for the seven flow conditions for which motion pictures were taken. This comparison shows that, for this range of flow conditions, experimental values of the dispersed water fraction are well within 30 per cent of the value predicted by Equation (5-25).

Figures 5.11 and 5.12 show the comparison of the calculated and measured values of the dispersed water fraction for all of the experimental conditions for which the inlet pressure was 90 psia. In Figure 5.11, all the data points which correspond to a particular air mass flow rate are given the same symbol. In Figure 5.12, all the data points which correspond to a particular water mass flow rate are given the same symbol. Figure 5.13 shows the comparison of the calculated and measured values of the dispersed water fraction for the flow conditions for which the inlet pressure was less than 90 psia.

Figures 5.11 through 5.13 show that most of the experimental values of the dispersed water fraction are within 30 per cent of the value predicted by Equation (5-25). For values of the dispersed water fraction greater than 0.10, the agreement is better than this. On the other hand, some values of the dispersed water fraction less than 0.10 are not within 30 per cent of the value predicted by Equation (5-25). In general, the latter data points correspond to the

FIGURE 5.10
 COMPARISON OF EXPERIMENTAL VALUES OF THE DISPERSED
 WATER FRACTION WITH EQUATION (5-25)

FIGURE 5.11
 COMPARISON OF EXPERIMENTAL VALUES OF THE DISPERSED
 WATER FRACTION WITH EQUATION (5-25)

5-29

FIGURE 5.12
 COMPARISON OF EXPERIMENTAL VALUES OF THE DISPERSED
 WATER FRACTION WITH EQUATION (5-25)

5-30

FIGURE 5.13

COMPARISON OF THE EXPERIMENTAL VALUES OF THE DISPERSED WATER FRACTION WITH EQUATION (5-25)

lowest air and water flow rates or to measurements made a short distance downstream of the water injection section.

On the basis of the comparisons shown in Figures 5.10 through 5.13, one can conclude that, except for a few values of the dispersed water fraction corresponding to the lowest air and water flow rates or to measurements made a very short distance downstream of the water injection section, the agreement between experimental values of the dispersed water fraction and Equation (5-25) is probably within the uncertainty which results from: (1) the assumptions made in the derivation of this equation, (2) the uncertainty of the experimental results used to determine the empirical constants and (3) the uncertainty of the values of W_G , W_L , P , and P_1 which correspond to a particular flow condition.

CHAPTER VI

COMPARISON OF THE EXPERIMENTAL RESULTS WITH
RESULTS REPORTED BY OTHERS

The purpose of this Chapter is to compare the experimental results presented in this thesis with the results of similar experiments reported by others. Since Equations (5-24) and (5-25) were derived from the experimental results presented in this thesis, these equations can be used for this comparison. However, it should be recognized that the constants in these equations are empirical and may not be generally valid. Therefore, before proceeding with the comparison, the range of flow conditions used to obtain the experimental results presented in this thesis will be discussed and some dimensionless quantities will be derived which can be used to characterize these conditions.

6.1 Discussion of the Flow Conditions Used for the
Experiments Described in this Thesis

The flow conditions used for the experiments described in this thesis were varied by independently changing the following: (1) the gas mass flow rate, (2) the liquid mass flow rate, and (3) the inlet pressure. In addition, observations and measurements were made at distances extending 130.25 in. or 262 diameters downstream of the water injection section. However, variables such as: (1) tube diameter, (2) gas and liquid properties, and (3) the design of the liquid injection section were not changed.

With respect to tube diameter, the question arises as to whether the constants in Equations (5-24) and (5-25) are actually a function of this variable. In particular, it is possible that the

constant, 17.65, in the exponential part of Equation (5-24) depends on tube diameter in such a way that $\frac{dw_d}{dz}$ is a function of Z/D rather than Z .

The constants, 0.07 and 12.8, in Equation (5-25) include the value of B_0 defined by Equation (5-6). Therefore, they are probably a function of surface tension. In addition, this property and others such as liquid density and viscosity may be important in characterizing a particular range of flow conditions, as discussed in Section 6.2 below.

The constants, 0.07 and 12.8, also include the value of the quantity, $B_4(Z)$, defined by Equation (5-17). As discussed in Chapter V, the variation of $B_4(Z)$ along the tube is a result of the wave agglomeration process. However, near the inlet, this process is probably influenced by the design of the liquid injection section. For this reason, values of $B_4(Z)$ near the inlet might be different if, for example, the liquid is injected into the tube through an annular slot instead of a porous wall. Such an effect would result in different values of the constants in Equation (5-25).

Finally, since experimental measurements and observation were limited to a distance of 262 diameters downstream of the water injection section, the constants in Equation (5-25) might not be valid at distances greater than this. In fact, since liquid is being torn from the disturbance waves as they move downstream, one would expect that the wave frequency would eventually decrease because of entrainment. On the other hand, the motion pictures show that, at large distances from the water injection section, small disturbances often form in the wake of a particular wave. These disturbances are then

absorbed by the next wave. Since this process could provide a means of replenishment of the waves as they move along the tube, a considerable distance may be required before changes in wave frequency due to entrainment would be significant.

6.2 Development of Dimensionless Quantities Which Can be Used to Characterize a Particular Range of Flow Conditions

In annular gas-liquid flow, the surface condition of the liquid film can be influenced by forces due to: (1) the axial pressure gradient, (2) gravitational attraction, (3) interfacial surface tension, and (4) liquid viscosity. The pressure gradient force is impressed upon the film by the dispersed phase by means of a shear force at the interface. Since this force is responsible for the motion of the liquid film in upwards annular flow, its influence can never be neglected. However, under certain conditions, the influence of one or more of the other three forces may be of comparable or greater significance. When this is the case, the character of the experimental results and correlations describing them would probably also change. Therefore, even if the effect of all the important variables were included in Equation (5-25), this equation still might not correlate measurements of the dispersed liquid fraction for all annular flow conditions. For this reason, some dimensionless quantities will be developed which can be used to indicate the importance of these forces relative to the pressure gradient or interfacial shear force for a particular range of flow conditions.

The pressure gradient and gravitational forces acting on a typical element of the liquid film are shown in Figure 6.1. The

FIGURE 6.1
PRESSURE GRADIENT AND GRAVITATIONAL FORCES

6-5

relative importance of these forces can be expressed by the following dimensionless quantity:

$$N_G = \frac{|dP/dZ|}{\rho_L g/g_c} \quad (6-1)$$

where ρ_L is the liquid density (lb_m/ft^3).

The surface tension forces acting on an element of the film surface is shown in Figure 6.2. Assuming that, on the average, one of the radii of curvature is of the same order of magnitude as the tube diameter and that the other is essentially infinite, the following expression can be written for the force per unit area due to surface tension:

$$S = \frac{2\sigma}{D} \quad (6-2)$$

where σ is the surface tension (lb_f/ft). The interfacial shear force per unit area is approximately related to the pressure gradient by Equation (5-9). If it is assumed that $D_c \approx D$, and that $B_1 \approx 1$, this equation becomes:

$$\tau_1 \approx \left| \frac{dP}{dZ} \right| \frac{D}{4} \quad (6-3)$$

Thus, a dimensionless quantity which indicates the importance of the interfacial shear or pressure gradient force relative to the surface tension force can be expressed approximately as follows:

$$N_{ST} = \frac{\left| \frac{dP}{dZ} \right| D^2}{8\sigma} \quad (6-4)$$

In single-phase flow, the importance of viscous forces relative to pressure gradient or inertial forces is generally expressed by a Reynolds number. It seems reasonable, therefore, to use a similar quantity to indicate the relative importance of these forces within

FIGURE 6.2
SURFACE TENSION FORCE

the liquid film in annular flow. A film Reynolds number can be defined as follows:

$$(N_R)_f = \frac{\rho_L v_f \delta}{\mu_L} \quad (6-5)$$

where δ is the average film thickness (ft) and μ_L is the liquid viscosity (lb_m/ft hr). Since

$$W_f = \rho_L v_f \pi D \delta, \quad (6-6)$$

Equation (6-5) can also be written as follows:

$$(N_R)_f = \frac{W_f}{\pi D \mu_L} \quad (6-7)$$

where W_f is the film mass flow rate (lb_m/hr).

The dimensionless quantities defined by Equations (6-1), (6-4) and (6-7) were calculated for each of the flow conditions used to obtain the results correlated by Equation (5-25). This was done using the computer program described in Appendix E, Section E.3. The range of values for each of these quantities was the following:

$$N_G = 0.258 \text{ to } 4.76$$

$$N_{ST} = 1.05 \text{ to } 12.70$$

$$(N_R)_f = 197 \text{ to } 1650$$

6.3 Comparison of the Experimental Results with Results Reported by Gill

Prior to the beginning of the experimental work described in this thesis, experimental measurements of the variation of the dispersed water fraction with distance along a vertical tube for annular air-water flow were reported by Gill, et al. (12). This experiment and the results which were obtained are described in Chapter II. The

flow condition which was used is compared with the annular to semi-annular transition in Figure B.3 of Appendix B. The range of values of the dimensionless quantities defined by Equations (6-1), (6-4), and (6-7) was the following:

$$N_G = 0.459 \text{ to } 0.639$$

$$N_{ST} = 7.79 \text{ to } 10.6$$

$$(N_R)_f = 615 \text{ to } 1290$$

It can be seen that the value of each of these quantities was within the range of values corresponding to the flow conditions used for the experiments described in this thesis.

The variation of the dispersed water fraction and total pressure drop with distance from the water injection section is shown in Figures 2.2 and 2.3 in Chapter II. A comparison of these graphs with Figures 4.1 through 4.6 in Chapter IV shows that the variations obtained by Gill, et al. were similar to those obtained in the experiments described in this thesis. However, there is an important quantitative difference. Figure 2.2 shows that, for the experiment reported by Gill, et al, the rate of increase of the dispersed water fraction with distance along the tube became approximately constant at a distance of 12 ft downstream of the water injection section. On the other hand, the experimental results described in Chapter IV of this thesis show that, for a particular flow condition, the rate of increase with distance became approximately constant at a distance of 5 ft downstream of the water injection section.

In its present form, Equation (5-24) is not in agreement with the result obtained by Gill, et al. However, as pointed out in

Section 6.1, the constant in the exponential part of this equation may be a function of tube diameter. In particular, if it is assumed that this constant is inversely proportional to tube diameter, the distance required for the rate of increase of the dispersed water fraction to become approximately constant along the tube would be proportional to the tube diameter. The fact that the tube diameter used by Gill, was 1.25 in., compared to 0.497 in. for the experiments described in this thesis, would then explain the observed difference in the distance required for the rate of increase of the dispersed water fraction along the tube to become approximately constant.

On the basis of the above reasoning, it will be assumed that Equation (5-24) should be more generally written:

$$\frac{dW_d}{dz} = \left| \frac{dP}{dz} \right| \frac{1}{P} W_G W_L^{0.5} \left[0.070 + 0.72 e^{-\frac{z}{35.5D}} \right] \quad (6-8)$$

If this expression is integrated as described in Section 5.4 of Chapter V, the following equation is then obtained:

$$\frac{W_d}{W_L} = \frac{W_G}{W_L^{0.5}} \left| \frac{\ln P/P_1}{z/D} \right| \left[0.070 z/D + 25.6 \left(1 - e^{-\frac{z}{35.5D}} \right) \right] \quad (6-9)$$

For a tube diameter of 0.497 in., this equation reduces to Equation (5-25). Thus, Equation (6-9) can be considered to have the same empirical relationship to the results of the experiments described in this thesis as does Equation (5-25).

Equation (6-9) was used to calculate values of the dispersed water fraction corresponding to experimental values of this quantity calculated from the data reported by Gill. The results of this

calculation are shown in Figure 6.3. It can be observed that the experimental values of the dispersed water fraction obtained by Gill are in very good agreement with the values calculated from Equation (6-9). Thus, assuming that the effect of tube diameter is correctly included in Equation (6-9) it can be concluded that the experimental results reported by Gill are in good agreement with the experimental results presented in this thesis.

6.4 Comparison of the Experimental Results with Results Reported by Cousins

More recent experimental measurements of the variation of the dispersed water fraction with distance along a vertical tube for annular air-water flow have been reported by Cousins, et al. (8). For these experiments, the tube had an inside diameter of 0.375 in. As in the case of the experiment reported by Gill, et al. (12) and the experiments described in this thesis, air was forced through the tube from the bottom and water was injected radially through a porous bronze wall section. A calming length of approximately 3 ft was provided between the air inlet and the water injection section.

Experimental conditions were varied by independently changing the air and water mass flow rates. The air mass flow rate was varied from 40 to 70 lb/hr. The water mass flow rate was varied from 5 to 230 lb/hr. The inlet pressure was held constant at 40 psia. The temperatures of the air and water were approximately equal to the ambient temperature. The particular experimental conditions which were used are compared with the semiannular to annular flow regime transition in Figure B.3 of Appendix B. The range of values of the dimensionless quantities given by equations (6-1), (6-4) and (6-7)

6-11

FIGURE 6.3

COMPARISON OF VALUES OF THE DISPERSED WATER FRACTION FROM DATA OBTAINED BY GILL (12) WITH EQUATION (6-9)

were as follows:

$$N_G = 0.210 \text{ to } 7.24$$

$$N_{ST} = 0.319 \text{ to } 11.0$$

$$(N_R)_f = 21.5 \text{ to } 988$$

It can be seen that the range of value of these quantities overlaps to some extent the range of values for the flow conditions used in the experiments described in this thesis. Those flow conditions for which the values do fall within this range are indicated by shaded symbols in Figure B.3.

Measurements of the dispersed water and film mass flow rate were made at 11 different positions extending to 216 in. downstream of the water injection section. This was done using a porous bronze film removal section similar to the one used for the experiments described in this thesis. The pressure drop between the inlet and various positions downstream of the water injection section was also measured. This was done using a water purged manometer system.

Typical results, obtained for flow conditions for which the values of N_G , N_{ST} , and $(N_R)_f$ are within the range corresponding to the flow conditions used for the experiments described in this thesis, are shown in Figure 6.4 through 6.7. These results show considerably more scatter than the results obtained in the present experiments which are shown in Figure 4.1 through 4.6 and results obtained by Gill, et al. (12), shown in Figures 2.2 and 2.3. In addition, the results obtained by Cousins, et al. (8), which are shown in Figure 6.5 do not indicate the dispersed water fraction to be independent of water mass flow rate as do the results obtained in the experiments described in this thesis

EFFECT OF AIR MASS FLOW RATE ON THE DISPERSED WATER FRACTION ACCORDING TO DATA OBTAINED BY COUSINS (8)

FIGURE 6.5

EFFECT OF WATER MASS FLOW RATE ON THE DISPERSED WATER FRACTION
 ACCORDING TO DATA OBTAINED BY COUSINS (8)

FIGURE 6.6
EFFECT OF AIR MASS FLOW RATE ON PRESSURE DROP ACCORDING TO
DATA OBTAINED BY COUSINS (8)

FIGURE 6.7

EFFECT OF WATER MASS FLOW RATE ON PRESSURE DROP ACCORDING
TO DATA OBTAINED BY COUSINS (8)

which are shown in Figure 4.3. However, for a particular experimental condition, the variations of both dispersed water fraction and total pressure drop with distance along the tube indicated by the experimental results obtained by Cousins were similar to the variations observed in the experiment of Gill and in the present experiments. Quantitatively, the results obtained by Cousins which are shown in Figure 6.4 and 6.5 indicate that the rate of increase of the dispersed water fraction with distance along the tube became approximately constant at distances greater than 3 to 4 ft downstream of the water injection section. Since the tube diameter used by Cousins was 0.375 in. or approximately 0.75 times the diameter used for the experiments described in this thesis, this result is in good agreement with the dependence of $\frac{dW_d}{dz}$ on Z/D predicted by Equation (6-9). It is also of interest to note that the results obtained by Cousins which are shown in Figure 6.4 and 6.5 indicate that the dispersed water fraction continues to increase monotonically at distances extending to 216 in. or 576 diameters downstream of the water injection section.

The flow conditions used in the experiments reported by Cousins, et al. which do not fall within the range of values of N_G , N_{ST} , and $(N_R)_f$ corresponding to the experiments described in this thesis, involved low water flow rates. For the lowest water flow rates, entrainment did not occur at all. For somewhat higher water flow rates, entrainment occurred but did not start at the inlet. The distance downstream of the water injection section at which entrainment did begin decreased and approached zero as the water flow rate increased. For flow conditions such that N_G , N_{ST} , and $(N_R)_f$ were

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within the range corresponding to the experiments described in this thesis, the water mass flow rates were such that entrainment began at the inlet. This is probably because, for these conditions the disturbance waves form a very short distance downstream of the water injection section.

Equation (6-9) was used to calculate values of the dispersed water fraction corresponding to values of this quantity determined from the data reported by Cousins, et al. In view of the fact that this equation assumes that disturbance waves develop and entrainment begins immediately downstream of the water injection section, this calculation was limited to those flow conditions for which the values of N_G , N_{ST} , and $(N_R)_f$ were within the range corresponding to the flow conditions used for the experiments described in this thesis. The results of this calculation are shown in Figure 6.8. It can be observed that the experimental values of the dispersed water fraction are consistently lower than the value predicted by Equation (6-9). Therefore, assuming that the effect of tube diameter is correctly included in Equation (6-9), it must be concluded that the results reported by Cousins, et al. (18) are not in good agreement with the experimental results reported in this thesis.

Except for the disagreement shown in Figure 6.8, Equation (6-9) has been shown to be in good agreement with experimental results obtained for a wide range of flow conditions. The experiments reported in this thesis included variations of air mass flow rate, water mass flow rate and inlet pressure. In addition, the experiment reported by Gill, et al. (12) involved a larger tube diameter.

FIGURE 6.8

COMPARISON OF VALUES OF THE DISPERSED WATER FRACTION FROM DATA OBTAINED BY COUSINS (8) WITH EQUATION (6-9)

Furthermore, the method of water injection used for the experiments reported by Cousins was the same as the method used for the experiments described in this thesis and for the experiments reported by Gill. Therefore, the reason for the disagreement shown in Figure 6.8 cannot be explained at this time.

In addition to the results discussed above, Cousins, et al. (8) also reported experimental results which show that turbulent eddy transport of droplets from the dispersed phase to the film was significant for the range of flow conditions which were used. The rate of deposition was determined by removing the water film at a distance sufficiently far from the water injection section so that the flow was well established, and then following the subsequent build up of a new water film. In addition, measurements were made of the rate of interchange of water between the film and the dispersed phase by adding fluorescein dye to the film at a particular position downstream of the inlet and then measuring the dye concentration at various distances further downstream. The results of the dye mixing experiments indicated mass interchange rates in the range from 100 to 300 lb/hr ft² compared to values of the net rate of water transport from the film of 10 to 30 lb/hr ft² for the same range of flow conditions. These results provide further and more direct evidence that the monotonic increase of the dispersed water fraction at large distances from the inlet is not a result of the fact that the rate of deposition is negligible compared to the rate of entrainment.

6.5 Comparison of the Experimental Results Obtained
from the Motion Pictures with Results Reported
by Hall-Taylor and Hewitt

An experimental study of the characteristics of the disturbance waves on the film surface in annular air-water flow has also been reported by Hall-Taylor and Hewitt (15). The quantitative results obtained by these authors are described below.

The experiments utilized a transparent tube with an inside diameter of 1.25 in. and a length of 22 ft. Air was forced through it from the bottom. As in the case of the experiments described in this thesis and the experiments described by Gill, et al. (12) and by Cousins, et al. (8), water was injected radially through a porous wall section. A calming length of approximately 6 ft was provided between the air inlet and the water injection section. The air mass flow rate was varied between 124 and 373 lb/hr. The water mass flow rate was varied between 65 and 209 lb/hr. The inlet pressure varied between 16.4 and 23 psia. The temperature of the air and water were approximately equal to the ambient temperature. The particular experimental conditions which were used are compared with the annular to semiannular flow regime transition in Figure B.4 of Appendix B. The range of values of the dimensionless quantities given by Equations (6-1), (6-4), and (6-7) were:

$$N_G = 0.0429 \text{ to } 0.136$$

$$N_{ST} = 0.727 \text{ to } 2.3$$

$$(N_R)_f = 160 \text{ to } 480$$

It can be seen that only N_{ST} and $(N_R)_f$ overlap the range of values of

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these quantities corresponding to the flow conditions used in the experiments described in this thesis.

For each experimental condition, the tube was illuminated tangentially and the flow photographed by means of a 32 frame/sec, 35 mm camera. The camera was mounted so that nearly the whole length of the tube was included on each frame. After development, the films were analyzed using a single frame projector. Measurements were made of velocity, separation time and separation distance of the waves. These measurements were made over a section of the tube extending from 8 ft to 20 ft downstream of the water injection section.

The mean velocity of the disturbance waves varied from 4 to 10 ft/sec compared to a superficial air velocity of 40 to 150 ft/sec. As in the case of the experiments reported in this thesis, Hall-Taylor and Hewitt found that wave velocity increased roughly in proportion to the air flow rate but was approximately independent of the water flow rate.

For a particular experimental condition, Hall-Taylor and Hewitt found that individual measurements of wave velocity were distributed about an average value. Similar results were obtained in the case of measurements of separation distance and separation time.

Values of mean wave frequency were calculated from the values of the mean separation time. The resulting values of frequency were in the range from 1 to 7 waves/sec. The results indicated that wave frequency increased in rough proportion to the water flow rate but was approximately independent of the air flow rate. This result is exactly opposite from the result obtained in the experiments

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described in this thesis. This could be due to the difference in flow conditions indicated by the range of values of N_G , N_{ST} , and $(N_R)_f$.

Although systematic measurements of the wave disturbance length were not made, Hall-Taylor and Hewitt stated that the value of this quantity ranged from 1/2 to 3 inches. For the experiments reported in this thesis, the corresponding range of values of this quantity was from 1/8 to 1-1/4 inches. Again, this difference could be related to the difference in the range of flow conditions.

Measurements of the dispersed water fraction were not made in the experiments reported by Hall-Taylor and Hewitt (15).

CHAPTER VII

REMARKS CONCERNING APPLICATION OF THE EXPERIMENTAL RESULTS
TO A PHENOMENOLOGICAL MODEL OF BURNOUT

At this point, it is possible to consider the application of the experimental results presented in this thesis to a phenomenological model of burnout for conditions of annular steam-water flow through a heated tube. This is done in the discussion which follows:

7.1 Description of the Model

Consider the case of a heated vertical tube which is cooled by a mixture of steam and water entering at the bottom in forced convection. Assume that the flow regime at the inlet to the heated section is annular flow. Assume also that the fractional change in pressure along the tube is small and that the flow is turbulent in both the water film and the dispersed phase. For these conditions, the bulk temperature of the mixture of water droplets and steam in the dispersed phase should be equal to the saturation temperature and should remain essentially constant along the heated length. In addition, the temperature distribution across the core and including the turbulent surface layer of the water film should be nearly uniform. As a result, heat transfer by: (1) convection within the dispersed phase, (2) evaporation of water droplets, and (3) exchange of water droplets between the water film and the dispersed phase should be negligible. Therefore, essentially all of the heat transfer should be due to convection within the water film and to evaporation at the film surface or nucleate boiling.

On the basis of the above reasoning, the law of conservation

7-2

of mass can be applied to the control volume shown in Figure 7.1 to obtain the following equation for the decrease of the mass flow rate of the film over a distance, $d\ell$.

$$dW_f = \frac{dQ}{h_{fg}} - dW_d \quad (7-1)$$

where dQ is the power (BTU/hr) transferred to the mixture over the distance, $d\ell$, and h_{fg} is the enthalpy of vaporization (BTU/lb_m).

The first term on the right side of this equation is the decrease of the film flow rate due to evaporation or boiling and the second term is the decrease due to the net transport of water from the film as a result of entrainment and deposition. From this equation, an expression for the mass flow rate of the film at the end of the heated section of the tube can be obtained by integration. The result is:

$$W_{f_2} = W_{f_1} - \left[\frac{Q}{h_{fg}} + (W_{d_2} - W_{d_1}) \right] \quad (7-2)$$

where

$$Q = \int_0^H \phi \pi D d\ell \quad (7-3)$$

In Equation (7-2), the subscript 1 refers to the inlet to the heated section and the subscript 2 refers to the end of the heated section. In Equation (7-3), ϕ is the local heat flux (BTU/hr) and H is the total heated length (ft).

Equation (7-2) shows that, for a fixed inlet condition, the exit film flow rate decreases as the power is increased. Eventually, a dry patch should develop near the end of the heated length and a burnout transition would occur. If boiling is fully developed, this

FIGURE 7.1
CONTROL VOLUME USED TO DERIVE
EQUATION (7-1)

7-4

might occur as a result of a local film disruption due to steam bubbles breaking through the film surface. However, for flow conditions and heat flux distributions such that boiling is partially or completely suppressed, experimental results reported by Hewitt, et al. (17), (18) indicate that the transition results from a uniform decrease of the exit film flow rate to approximately zero. Therefore, for such conditions, it should be possible to use the following criterion to describe the burnout condition¹:

$$\begin{aligned} Q &= Q_c \\ \text{when} \\ W_{f2} &= 0 \end{aligned} \quad (7-4)$$

and, by using Equation (7-2), one can write the following expression for the critical power:

$$\begin{aligned} Q &= Q_c \\ \text{when} \\ \frac{Q}{h_{fg}} &= W_{f1} - (W_{d2} - W_{d1}) \end{aligned} \quad (7-5)$$

The quantities, W_{f1} and W_{d1} , in this equation are related to the total water mass flow rate entering the heated section by the following equation:

$$(W_{d1} + W_{f1}) = W_{L1} = W (1 - X_1) \quad (7-6)$$

¹Actually, the film would probably break down at a finite film flow rate. However, assuming that heat transfer and flow conditions in the film remain uniform around the circumference of the tube, this flow rate should be negligibly small.

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where W is the total mass flow rate (lb_m/hr) and X_1 is the inlet quality. Therefore, Equation (7-5) can also be written:

$$Q = Q_c$$

when

(7-7)

$$\frac{Q}{h_{fg}} = W(1 - X_1) - W_{d_2}$$

For the case of a uniform heat flux distribution along the heated length,

$$Q = \phi \pi D H$$

(7-8)

Thus Equation (7-7) can be alternatively written in terms of the critical heat flux as follows:

$$\phi = \phi_c$$

when

(7-9)

$$\frac{\phi \pi D H}{h_{fg}} = W(1 - X_1) - W_{d_2}$$

However, for the case of a non-uniform heat flux distribution, the integral nature of the processes leading to a burnout transition makes use of the term, critical heat flux, questionable; and one should probably refer instead to the critical power for such conditions.

The quantities, $W(1 - X_1)$ and h_{fg} , depend only on the total mass flow rate, the inlet quality, and the pressure. On the other hand, W_{d_2} is a function of the liquid phase distribution at the inlet to the heated section and the integrated effect of the entrainment and deposition processes which take place along the heated length. Therefore, in order to develop an expression for this quantity and expand Equations (7-7) and (7-9) into a form which can be used to correlate

burnout data, it is necessary to:

- 1) Specify the mass flow rate of the dispersed water at the inlet, W_{d1} , as a function of variables such as the total mass flow rate, inlet quality, pressure, and tube diameter.
- 2) Set up and solve a differential equation which relates the rate of change of the mass flow rate of dispersed water along the tube, $\frac{dW_d}{dl}$, to the entrainment and deposition processes.

The extent to which the experimental results presented in this thesis can provide information concerning these quantities is discussed below.

7.2 Remarks Concerning Application of the Experimental Results to the Model

The experimental results presented in this thesis, as well as the experimental results reported by Gill, et al. (12) and Cousins, et al. (8) show that, for a wide range of adiabatic flow conditions and tube lengths of practical interest, the mass flow rate of dispersed liquid continues to increase at large distances downstream of the inlet. As a result, the mass flow rate of dispersed liquid at a particular location along the tube should be regarded as an integral quantity which is a function of conditions existing and processes occurring upstream.

Therefore, for burnout experiments carried out under the conditions assumed in the derivation of Equations (7-7) and (7-9), the value of W_{d1} for a particular flow condition would probably depend on the method used to initially produce the steam-water mixture and the length of the unheated section provided upstream of the heated

section. This means that experimental results such as those presented in this thesis could not be used to provide information concerning this quantity unless a porous wall section was also used to initially mix the steam and water in the burnout experiments. If, however, such a mixing section were used, it might be possible to use these results to provide information concerning the functional dependence of W_{d1} on all variables except fluid properties and possibly tube diameter.

As a result of the dependence of W_{d1} on upstream conditions, burnout data obtained using a two-phase inlet condition would not be independent of the experimental apparatus being used. Therefore, unless W_{d1} is measured or otherwise known, burnout data of this type should be interpreted with caution.

It is of interest to note that Equations (7-7) and (7-9) could, in principle, be applied to the correlation of burnout data obtained with subcooled inlet conditions. Under these conditions, W_{d1} would be replaced by the mass flow rate of dispersed water at the position downstream of the inlet where the transition to annular flow occurs and the film loss mechanism becomes effective. In addition, the total heated length, H , in Equations (7-8) and (7-9) would be replaced by the part of the total heated length which is downstream of the position where the transition to annular flow occurs. However, for a particular flow condition and heat flux distribution, it is still necessary to determine the location along the tube where the transition to annular flow occurs and also to determine the corresponding liquid phase distribution; and present knowledge of this transition under non-adiabatic conditions is not adequate to do this.

For flow conditions and heat flux distributions such that nucleate boiling is not suppressed, Hewitt (17) observed that liquid entrainment at a particular position along the tube was to some extent due to the tearing of droplets from the film by vapor bubbles breaking through the film surface. In addition, under such conditions, it seems possible that burnout could occur before W_{f2} reaches zero because of film disruption. On the other hand, when boiling is suppressed, liquid mass transport from the film to the dispersed phase should be due to the net effect of the entrainment and deposition processes which occur in adiabatic flow and burnout should occur when W_{f2} becomes approximately equal to zero as assumed in the derivation of Equations (7-7) and (7-9). Under these conditions, it should therefore be possible to use experimental results of the type presented in this thesis to provide information concerning $\frac{dW_d}{dl}$.

Both the experimental results presented in this thesis and the experimental results reported by Gill et al. (12) and Cousins, et al. (8) show that, in adiabatic air-water flow, a considerable distance is required before the rate of increase of the mass flow rate of dispersed water along the tube reaches an approximately constant equilibrium value for a particular flow condition. Therefore, since in non-adiabatic flow the steam and water mass flow rates are changing continuously along the tube, it seems unlikely that $\frac{dW_d}{dl}$ for a particular flow condition along the heated length would correspond to the equilibrium value for the same flow condition under adiabatic conditions. On the other hand, the analysis and correlation of the experimental results presented in this thesis indicates that the rate of increase of the mass flow rate of dispersed water with

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distance along the tube is approximately proportional to the rate of energy transfer from the dispersed phase to the part of the film surface covered by disturbance waves. Furthermore, this relationship seems to correlate experimental data obtained near the inlet where the wave structure was changing almost as well as it correlates data obtained further downstream where the wave structure was not changing. Therefore, it should be possible to use such a relationship to determine local values of $\frac{dW}{d\ell}$ for steam-water flow through a heated tube. However, before this can be done, more knowledge is required of the effect of system variables on the wave structure on the surface of the liquid film under such conditions.

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

The principal conclusions which have been reached as a result of this study are outlined in the following discussion. In addition, recommendations are made regarding future work.

8.1 Conclusions Derived from the Experimental Results

The following conclusions are derived from the analysis and correlation of the experimental results presented in Chapter V and the comparison of these results with experimental results reported by Gill, et al. (12) and Cousins, et al. (8) as described in Chapter VI.

8.1.1 Conclusions Concerning Experimental Results Obtained for a Particular Flow Condition

The experimental results shown in Figures 4.1, 4.2 and 4.3 of Chapter VI show that, for a particular flow condition, the dispersed water fraction increases continuously with distance downstream of the water injection section. The motion pictures indicated that this is due to entrainment of water from the crests of disturbance waves by the air. Observations made with a stroboscope showed that disturbance waves develop within a few inches downstream of the water injection section for each of the flow conditions used for the experimental work described in this thesis.

Near the inlet, the rate of increase of the dispersed water fraction with distance along the tube decreases with distance from the water injection section. Results obtained from the motion pictures suggest that this decrease is partially due to a decrease in the rate of entrainment. In particular, as shown in Figures 5.2, 5.3 and 5.4, these results show that, for a particular flow condition, the average

fraction of the film surface covered by disturbance waves decreases along the tube. Therefore, the rate of entrainment should also decrease along the tube. However, as discussed in Chapter V, Section 5.4, the extent to which the rate of increase of the dispersed water fraction along the tube decreases near the inlet cannot be entirely explained in terms of a decrease in the rate of entrainment. For this reason, it is believed that, for a particular flow condition, the rate of deposition also increases significantly along the tube near the inlet. This would cause the rate of increase of the dispersed water fraction along the tube to decrease more rapidly with distance from the water injection section as was observed.

The decrease along the tube of the average fraction of the surface covered by disturbance waves was primarily a result of the decrease in wave frequency due to wave agglomeration. The latter process could be clearly observed in the motion pictures and was caused by the fact that waves which develop just above the water injection section have a distribution of velocities. Thus, faster waves are able to overtake and agglomerate with the slower ones.

The experimental results shown in Figures 4.1, 4.2, and 4.3 show that for a particular experimental condition, the dispersed water fraction at distances greater than 120 diameters downstream of the water injection section increases almost linearly along the tube. It is believed that this result indicates that, at large distances from the inlet, the rate of deposition is proportional to, but less than, the rate of entrainment and both rates remain approximately constant along the tube. Although the experimental results presented

in this thesis were limited to a distance of 262 diameters downstream of the water injection section, similar experimental results were obtained by Cousins, et al. (8) for distances extending to 576 diameters downstream of the water injection section.

8.1.2 Conclusions Concerning Correlation of the Experimental Results and Comparison with Experimental Results Obtained by Others

The nature of the entrainment process as observed in the motion pictures suggests that the rate of entrainment should be proportional to the rate of energy transfer from the air to the part of the film surface covered by disturbance waves. Starting with this assumption, it is possible to use the experimental results to derive a semi-empirical expression for the dispersed water fraction as a function of air mass flow rate, water mass flow rate, pressure, and distance downstream of the water injection section. This derivation is presented in Chapter V and the resulting expression is given by Equation (5-25). Except for a few values of the dispersed water fraction corresponding to the lowest air and water flow rates or to measurements made a very short distance downstream of the water injection section, the agreement between experimental values of the dispersed water fraction reported in this thesis and Equation (5-25) is believed to be within the uncertainty which results from: (1) the assumptions made in the derivation of the equation, (2) the uncertainty of the experimental results used to determine the empirical constants and (3) the uncertainty of the values of W_G , W_L , P_1 , and P which correspond to a particular flow condition and distance from the water injection section.

For annular gas-liquid flow, the surface condition of the liquid film can be influenced by forces due to: (1) the pressure

gradient, (2) gravitational attraction, (3) interfacial surface tension, and (4) viscosity of the liquid. The pressure gradient force is impressed upon the film by the interfacial shear force which is responsible for the motion of the liquid film. Therefore, it can never be neglected. However, under certain conditions, the influence of one or more of the other three forces could be of comparable or greater significance. When this is the case, the character of the experimental results and correlations describing them would probably also change. On the basis of this reasoning, dimensionless quantities can be derived which can be used to indicate the importance of these three forces relative to the pressure gradient or interfacial shear force for a particular range of flow conditions. This was done in Chapter VI and these quantities are given by Equations (6-1), (6-4), and (6-7). These quantities were then used to establish a basis for comparison of the experimental results presented in this thesis with similar experimental results reported by Gill, et al. (12) and Cousins, et al. (8).

The comparison of Equation (5-25) (which was semi-empirically derived from the experimental values of the dispersed water fraction which are reported in this thesis) with experimental results reported by Gill, et al. (12) indicates that the rate of increase of the dispersed water fraction with distance along the tube is a function of Z/D rather than Z . This conclusion led to the development of Equation (6-9) which is an equation for the dispersed water fraction which includes the effect of tube diameter. For a tube diameter of 0.497 in. this equation reduces to Equation (5-25).

The experimental results reported by Gill, et al. (12) are in

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good agreement with Equation (6-9) and therefore with the results reported in this thesis. However, experimental results reported by Cousins, et al. (8) are consistently lower than predicted by Equation (6-9) and are therefore not in agreement with the results presented in this thesis or the results reported by Gill.

8.2 Conclusions Regarding Application of the Experimental Results to a Phenomenological Model of Burnout

A phenomenological model of burnout for conditions of annular steam-water flow through a heated vertical tube is developed in Chapter VII. This model is based on the assumption that burnout occurs when the liquid film flow rate at the end of the heated length becomes approximately equal to zero as a result of evaporation and the net effect of the entrainment and deposition processes occurring upstream. Equations (7-7) and (7-9) are the resulting expressions for the critical heat flux.

In order to develop these equations for use in correlating data obtained from burnout experiments which utilize two-phase inlet conditions, it would be necessary to specify the mass flow rate of dispersed water at the inlet to the heated section. However, the experimental results presented in this thesis show that the mass flow rate of dispersed water in annular gas-liquid flow does not approach an equilibrium value for a wide range of flow conditions and tube lengths of practical interest. Therefore, in the case of the burnout experiments, the value of this quantity at the inlet of the heated section would probably depend on the method used to initially mix the steam and water upstream of this location. This means that the burnout data obtained would probably not be independent of the experimental

apparatus. Therefore, such data should be interpreted with caution unless the mass flow rate of dispersed water at the inlet to the heated section is measured or otherwise known.

For conditions such that nucleate boiling is suppressed, liquid mass transport from the film should be due to the net effect of the entrainment and deposition processes which occur in adiabatic flow. However, the experimental results presented in this thesis and the experimental results reported by Gill, et al. (12) and Cousins, et al. (8) show that, in adiabatic air-water flow, a considerable distance is required for the net rate of liquid mass transport from the film to reach an approximately constant equilibrium value for a particular flow condition. Therefore, since in non-adiabatic flow, the steam and water mass flow rates are changing continuously along the tube, it seems unlikely that the net rate of liquid mass transport from the film at a particular location along the heated length would correspond to the equilibrium value for the same flow condition under adiabatic conditions. On the other hand, the analysis and correlation of the experimental results indicates that, to a good approximation, the net rate of water mass transport from the film at a particular location along the tube is proportional to the rate of energy transfer from the air to the part of the film surface covered by disturbance waves. Since this relationship correlates results obtained under conditions where the wave structure was changing along the tube almost as well as it correlates data obtained for conditions where this structure was constant along the tube, it should, in principle, be possible to use it to determine local rates of liquid mass transport from the film in non-adiabatic flow.

8.3 Recommendations for Future Study

It is recommended that future study be directed toward obtaining a basic understanding of the following aspects of annular gas-liquid flow:

- 1) The wave structure at the interface between the liquid film and the dispersed phase.
- 2) Turbulent eddy transport of dispersed droplets.

It is believed that information of this type would be of considerable value in the further development of a phenomenological model of burnout such as the one described in Chapter VII.

With respect to the wave structure at the interface between the liquid film and the dispersed phase, it is recommended that effort be made to answer the following questions: (1) What is the detailed relationship between the disturbance waves and entrainment? (2) How should the disturbance wave structure be described? (3) What is the effect of system variables on this structure? (4) How is this structure related to the interfacial shear stress? (5) What is the effect of the waves on the scale of turbulence in the dispersed phase?

The results obtained from high speed motion picture photography which are presented in this thesis have provided some information regarding the first three of these questions. However, these experiments only cover a limited range of flow conditions. In addition, the information obtained is limited because the motion pictures only provided an external, two-dimensional view of the film. Therefore, it is recommended that the use of high speed motion picture photography be extended to a wider range of flow conditions and that an effort be made to develop an experimental technique which also pro-

vides information about the film profile.

An example of the sort of technique which might be used to obtain information of the latter type is described by Hewitt, et al. in reference (16). This method utilized a needle probe so that it could be located at any radial position. The maximum film thickness was determined by moving the needle toward the tube wall until the tip made contact with the waves on the film surface. When this occurred, current was observed to flow through film to a detection circuit connected to the tube wall. It was possible to obtain further information about the disturbance waves by measuring the contact frequency and the fraction of the time that contact was being made with the film as a function of position from the wall. However, it was pointed out by Hewitt (16) that there was a tendency for liquid to remain on the probe tip after a particular wave passed by. Therefore, unless a means can be developed to avoid this difficulty, results obtained using this method would have to be considered qualitative.

With respect to the study of turbulent eddy transport of dispersed droplets, it is recommended that future experimental work be directed at answering the following questions: (1) What is the size distribution of these droplets? What is the effect of system variables on this size distribution? (2) What is the velocity of the droplets relative to that of the gas? How does the velocity vary with droplet size and with position along the tube? (3) To what extent do the droplets follow the motion of turbulent eddies? (4) What is the relationship between the concentration of dispersed droplets and the scale of turbulence within the dispersed phase?

In order to obtain experimental information regarding these questions, it is necessary to develop an experimental technique which is capable of measuring the size and velocity of individual droplets. Results obtained from high speed photography by Cooper, et al. (7) indicate that dispersed droplets formed in annular air-water flow have a mean size in the range from 50 to 100 microns. Furthermore, for flow conditions such as used in the experiments described in this thesis, droplet velocities are probably in the range from 25 to 125 ft/sec. Therefore, it is clear that, in order to obtain experimental information concerning the size and motion of entrained droplets in annular flow, an experimental technique is required which is both sensitive and fast. This is a difficult experimental problem. However, its solution would represent a significant contribution to the study of annular gas-liquid flow.

Of the various experimental techniques which might be applied to the measurement of very small liquid droplets in a high velocity air stream, the one which appears to have the best chance of being successfully developed is high speed photography. Cooper, et al. (7) obtained some very good results for a limited range of conditions. However, there are several problems to be overcome. One is that elaborate optical and lighting equipment is often required. In addition, a considerable amount of effort is required in the analysis of the photographs; and, since this analysis is usually done manually, a great deal of human judgment may be involved.

APPENDIX AHEAT AND MASS TRANSPORT PROCESSES LEADING TO
BURNOUT IN STEAM-WATER FLOW

The following discussion is intended to give a qualitative picture of the heat and mass transport processes which are believed to lead to burnout for steam-water flow through a heated tube. Following to some extent the approach used by Collier (6), the discussion will consider the case of a long vertical tube which is heated by a low, uniform heat flux and cooled by water entering at the bottom in forced convection. See Figure A.1.

A.1 Heat and Mass Transport Processes Characteristic
of the Various Flow Regimes

In section 1 of the tube, the cooling water is assumed to be below the saturation temperature corresponding to the local pressure. For these conditions, heat transfer is by single-phase convection and the bulk water temperature increases linearly along the tube.

As the temperature of the water increases, the tube wall surface temperature also increases and approaches the saturation temperature. At the lower end of section 2, the wall temperature exceeds the saturation temperature by a few degrees and the water in contact with it is superheated by an amount sufficient to allow steam bubbles to form at favored points of nucleation. These bubbles grow and eventually become large enough to detach and travel into the cooler bulk stream, where they collapse. For some conditions, the steam bubbles may grow and collapse while still attached to, or even sliding along, the wall. This process is called subcooled nucleate boiling. The agitation induced by the formation of bubbles in the layer of superheated water

FIGURE A.1
STEAM-WATER FLOW THROUGH A UNIFORMLY
HEATED VERTICAL TUBE

A-3

near the wall greatly increases the heat transfer coefficient from its value in the single phase convection region. This quantity continues to increase with position along the tube as the bulk water temperature approaches the saturation temperature. On the other hand, the wall temperature remains approximately constant.

At the start of section 3, the bulk water temperature reaches the saturation temperature, and the steam bubbles formed at the wall no longer condense. Instead, they become dispersed in the water. This flow regime is called bubble flow. Although the heat transfer process at the wall is referred to as saturated nucleate boiling and results in net steam generation, it is essentially the same process as subcooled boiling. Furthermore, the heat transfer coefficient remains approximately equal to the highest value reached for the subcooled condition. Thus, the tube wall temperature in section 3 does not vary appreciably along the tube.

Within section 3, the mass flow rate of steam increases linearly along the flow path. Since the total mixture mass flow rate is constant, this change is conveniently expressed as an increase in the mixture quality. As the quality increases along the tube, the steam bubbles tend to agglomerate and decrease in number. In addition, they tend to move toward the tube axis as a result of forces produced by the unequal flow of water around them in the presence of the wall. These effects cause a transition to slug flow. This flow regime is characterized by large, bullet-shaped steam bubbles separated by slugs of water containing smaller bubbles. The heat transfer mechanism within the section of the tube where slug flow develops is probably a combination of nucleate boiling and surface evaporation of the water at the

boundaries of the large bubbles.

As the quality increases along the tube and section 4 is approached, a transition to annular flow occurs. Experimental observations made by Griffith (13) and by Haberstroh (14) indicate that, in the initial stages of this transition, the water slugs decrease in length and tend to contain more steam bubbles. As the quality increases, the slugs begin to oscillate irregularly and, in some cases, they collapse and fall backward toward the tube wall. This transitional flow regime is usually referred to as ~~semiannular~~ or churn flow. As the quality increases further, most of the water moves to the wall and the transition is completed.

It seems likely that, under some conditions, a transition could take place directly from bubble to annular flow within section 3 of the tube. This is because, as pointed out by Moissis and Griffith (25), the development of slug flow can require considerable distance along the tube. Furthermore, the bubble agglomeration process which causes this development would probably be retarded if the difference between the densities of the phases is small or if the turbulent intensity is large. Thus, for a particularly high rate of change of quality with distance along the tube or for sufficiently high pressure or total mass flow rate, slug flow might not develop.

The heat and mass transport processes which occur in annular flow have been discussed by Lacy, et al. (23) and by Hewitt, et al. (17), (18). This flow regime is characterized by the fact that part of the water flows in a thin, wavy film which moves along the wall under the influence of the faster moving steam. The remaining water is dispersed in the steam. At the lower end of section 4, most of the water probably

flows in the film. However, as the steam velocity increases along the tube, water is entrained from the film and the dispersed water fraction increases.

For a sufficiently high heat flux, experimental observations made by Hewitt, et al. (17) indicate that nucleate boiling may occur to a significant extent near the lower end of section 4. However, at the upper end, this process may be partially or completely suppressed. This phenomenon is believed to be related to the fact that packets of water at a temperature close to the saturation temperature are continuously being transported from the turbulent surface layer of the film to its laminar sublayer. As the quality increases, the average velocities of the dispersed phase and the water film increase and the thickness of the laminar sublayer decreases. Thus, it becomes more and more possible for these packets of water to reach the small bubbles growing on the heated surface and to maintain the local water temperature below that which is necessary for further growth of these bubbles. As a result, nucleate boiling is suppressed. When this is the case, heat is probably transferred only by convection within the film and by evaporation at the film surface. For these conditions, the heat transfer coefficient is very high and increases steadily with quality.

A.2 Flow Regime Transitions

For the system described above, the primary variable influencing the flow regime transitions is the quality. The problem of specifying the quality corresponding to the various transitions for a given pressure, tube diameter and total mass flow rate is a difficult one and has not yet been adequately solved. However, it is possible to do this for a limited range of conditions by using experimental

observations of these transitions. This has been done by Bennett, et al. (3) for steam-water flow through a 0.497 in. electrically heated tube at pressures of 500 and 1000 psia. The results are shown in Figures A.2 and A.3 as a function of quality and total fluid mass velocity. The regimes were identified by taking high speed motion pictures of the flow emerging from the end of the heated section into a glass tube of equal diameter and by taking X ray photographs through a part of the heated section which was made of titanium. It is interesting to note that these observations indicated, for annular flow at high total mass velocities, that the dispersed water flows in a segregated manner as frothy lumps. Bennett referred to this condition as "wispy-annular".

The principle observation to be made from Figures A.2 and A.3 is that, for total mass velocities exceeding 5×10^5 lb/hr ft² and pressures as high as 1000 psia (which includes conditions for which much of the burnout data have been obtained), the annular flow regime exists over most of the quality range.

A.3 Mechanisms of Burnout

For subcooled and low quality flow conditions, burnout is probably caused by a transition to film boiling as shown in Figures A.4 and A.5. As the heat flux is increased from the initial conditions shown in these figures, the number of nucleation centers increases. However, since heat is primarily transported by local convection between the bubbles and this process is being more and more restricted, the heat removed per nucleation center decreases. As the heat flux is increased further, the nucleation centers become so closely spaced that the bubbles begin to interfere with one another. Although the nature of

FIGURE A.2
FLOW REGIME DIAGRAM CONSTRUCTED FROM OBSERVATIONS OF
STEAM-WATER FLOW AT 500 psia (BENNETT, et al. 3)

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FIGURE A.4

BURNOUT FOR SUBCOOLED FLOW CONDITIONS

FIGURE A.5
BURNOUT FOR LOW QUALITY FLOW CONDITIONS

the interaction is not positively known, it has been suggested by Zuber (35) that the bubbles join to form continuously oscillating vapor columns near the heated surface. When the burnout heat flux is reached, the interaction between these vapor columns is sufficient to cause the area of the heated surface between them to become blanketed with steam. This results in an almost instantaneous transition to film boiling.. For this condition, heat must be transferred from the tube surface across a vapor film by conduction and radiation. Since heat transfer coefficients characteristic of this process are very low, the final temperature of the tube wall can be orders of magnitude higher than before the transition occurred and physical failure usually results.

For medium and high quality flow conditions, burnout probably results from a loss of the water film as shown in Figure A.6. As the heat flux is increased from the initial condition shown in this figure, the film flow rate at the tube exit gradually decreases. This decrease is a result of boiling or evaporation and of mass transport of water from the film as a result of the shear force exerted on its surface by the high velocity steam. In addition, when nucleate boiling is not suppressed, Hewitt (17) has observed that water can be torn from the film by bubbles breaking through the film surface. As the heat flux is increased further, the combined effect of evaporation and liquid mass transport will eventually cause a dry wall condition at or near the end of the heated length. Hewitt (17), (18) has suggested that, for flow conditions and heat transfer rates such that nucleate boiling is partially or completely suppressed, this occurs as a result of a gradual decrease of the film flow rate to approximately zero at the end of the heated length. On the other hand, Todreas (31) has suggested

FIGURE A.6
BURNOUT FOR MEDIUM AND HIGH QUALITY
FLOW CONDITIONS

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that, for flow conditions and heat transfer rates such that nucleate boiling is not suppressed, a dry wall condition could also occur as a result of local film disruption caused by the bubbles breaking through the film surface. In either case, when the burnout heat flux is reached, a permanent dry patch is formed and heat transfer must then be by convection to the dispersed phase and by evaporation of droplets striking the tube wall. Parker and Grosh (26) have found experimentally that, for these conditions, heat transfer coefficients are very low. As a result, the wall temperature may rise several hundred degrees and cause physical failure of the tube.

APPENDIX B

THE ANNULAR TO SEMIANNULAR FLOW REGIME TRANSITION
IN ADIABATIC, AIR-WATER FLOW

When a mixture of gas and liquid flows through a vertical tube, the phases will assume one of the four basic flow regimes shown in Figure 2.1 of Chapter II.

The analysis of any two-phase flow problem must begin with a specification of the flow regime. As a result of this fact, many investigators have directed considerable effort toward the development of a useful graphical representation of the transitions between these regimes. With respect to the study presented in this thesis, the transition between the annular and semiannular flow regimes is of particular interest since it defines the range of conditions for which annular flow can exist as a fully developed regime.

B.1 Experimental Work of Haberstroh

The annular to semiannular transition has been recently studied by Haberstroh (14) for gas-liquid flow upwards through an unheated vertical tube. In order to detect the transition, he used a conductance probe developed by Solomon (30). This probe utilizes the difference between the electrical conductivity of the gas and liquid to indicate the presence of liquid bridges from the tube centerline to the wall. It therefore characterizes the transition as a change from a phase distribution for which the gas phase is continuous (annular flow) to one for which the liquid phase is continuous (semiannular flow).

The annular to semiannular transition lines determined by Haberstroh for air-water flow conditions are shown graphically in Figure B.1 in terms of the following variables:

$$V_G^* = \frac{V_{GS}}{\sqrt{\frac{\rho_L}{\rho_G}} \sqrt{gD}} = \frac{\frac{W_G}{\rho_G A}}{\sqrt{\frac{\rho_L}{\rho_G}} \sqrt{gD}} \quad (B-1)$$

$$V_L^* = \frac{V_{LS}}{\sqrt{gD}} = \frac{\frac{W_L}{\rho_L A}}{\sqrt{gD}} \quad (B-2)$$

These transition lines give the minimum value of V_G^* for which annular flow was observed for a given value of V_L^* .

It should be noted that the determination of the transition involved a visual interpretation of the probe output. Therefore, each of the transition lines shown in Figure B.1 has an inherent uncertainty. However, the lack of agreement between these lines is somewhat more than would be expected. Haberstroh suggested that this disagreement might be due to the influence of entrance effects on the results obtained for the 1.0 in. and 1.5 in. tubes.

Figure B.1 shows that, for the 0.5 in tube, a break was observed in the transition line at a value of V_L^* equal to 1.4. A similar break was also observed for several other gas-liquid flow conditions not shown in Figure B.1. After rechecking these results, Haberstroh concluded that this phenomenon was a real one and was not due to the design of the experimental apparatus. However, the physical reason for it is not clear, and this part of the transition line deserves further study.

FIGURE B.1

ANNULAR TO SEMIANNULAR TRANSITION LINES FOR AIR-WATER
FLOW THROUGH A VERTICAL TUBE (HABERSTROH 14)

Finally, with respect to the use of the quantities V_G^* and V_L^* in Figure B.1, it is of interest to note that these quantities have also been used by Wallis (33) to correlate experimental observations of the "flooding point" for counter current gas-liquid flow in vertical tubes. Wallis has suggested (34) that this phenomenon is similar to the transition from annular to semiannular flow in cocurrent flow, particularly at liquid flow rates approaching zero. Therefore, the use of these quantities to correlate observations of this transition seems to have a logical basis.

B.2 Comparison of Experimental Conditions with the Transition Lines Obtained by Haberstroh

The flow conditions used for the experiments reported in this thesis and for similar experiments reported by Gill, et al. (12), Cousins, et al. (8), and Hall-Taylor and Hewitt (15) are compared with the transition lines obtained by Haberstroh (14) in Figures B.2 through B.4.

FIGURE B.2
FLOW CONDITIONS USED FOR THE EXPERIMENTS
REPORTED IN THIS THESIS

FIGURE B.3
 FLOW CONDITIONS USED BY GILL, et al. (12) AND
 COUSINS, et al. (8)

FIGURE B.4
FLOW CONDITIONS USED BY HALL-TAYLOR
AND HEWITT (15)

APPENDIX C

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DETAILS OF THE EXPERIMENTAL APPARATUS

C.1 Compressors and Associated Equipment

Air was supplied to the hydraulic system by an Ingersol-Rand, Type XRB-NL, horizontal, two-stage, non-lubricated, reciprocating compressor capable of delivering 450 scfm of air at 125 psig. It was equipped with an intercooler and aftercooler utilizing city water as the coolant. City water was also used as a coolant for the air cylinders. A receiver was located immediately downstream of the aftercooler. Air from the receiver passed through a length of 2 in. pipe, another receiver, and then an additional length of 2 in. pipe before entering the hydraulic system. The compressor capacity was controlled by a free-air regulator which was set to unload the compressor air cylinders when the discharge pressure reached 97 psig and load them again when the discharge pressure dropped to 94 psig. Therefore, in order to maintain a steady flow rate, it was necessary to bleed air from the 2 in. supply pipe at a rate sufficient to keep the discharge pressure below 97 psig and the air compressor cylinders loaded. The bleed rate could be adjusted by means of three valves located in pipes branching from the 2 in. pipe. The size of these valves was such that two could be used for coarse adjustment and one for fine adjustment.

Water was forced into the test section using compressed air supplied from two, Ingersol-Rand, two-stage, oil-lubricated compressors connected in parallel. One was capable of delivering 50 scfm of air at 100 psig. The other was capable of delivering an unknown but

smaller flow rate at 100 psig. The cylinders of each of these compressors were cooled by natural circulation of ambient air. A receiver was located on the discharge side of each compressor. Operation of each compressor was intermittent and regulated to maintain the pressure in the receivers between 95 and 120 psig.

C.2 Coolers

The air and water coolers were identical. Each was a copper, shell-and-tube heat exchanger containing 56 tubes. These tubes had an inside diameter of 3/16 in., an outside diameter of 1/4 in. and an approximate length of 14 in.

C.3 Filters

The air filter located just upstream of the entrance to the test section was a Cuno Model no. 1B2G filter. The housing was made of cast iron and steel and contained a Cuno no. 2278-B3 Micro-Klean, cellulose cartridge with a nominal rating of 5 microns.

The filter located in the supply line for the air used to force water into the vertical tube was a Cuno Model no. 1B1G filter. The housing was made of the same materials as the 1B2G filter. However, it was smaller and contained a Cuno no. 2215-B3 Micro-Klean cartridge. This cartridge was also made of cellulose and had a nominal rating of 5 microns.

The filter located between the water supply tank and the rotameter was a Cuno Model no. 1C1 filter. The housing was made of cast aluminum and contained a Cuno no. 2230-B3 Micro-Klean cartridge. This cartridge was also made of cellulose and had a nominal rating of 5 microns.

The water filter located just upstream of the entrance to the water injection section was a Cuno Model no. 1B1 filter. The housing was made of cast bronze and contained a Cuno no. 50155 recleanable Poro-Klean element. This element was made of sintered stainless steel and also had a nominal rating of 5 microns.

C.4 Flow Measurement Apparatus

C.4.1 Apparatus for Measurement of Air Flow Rate to the Test Section

The air flow rate to the test section was determined by measuring the pressure drop across a square-edged orifice plate mounted in a straight section of steel pipe. The diameter of the orifice was 0.500 in. and the inside diameter of the pipe was 2.067 in. Pressure taps were located in flanges approximately 1 in. upstream and downstream of the orifice plate. The air pressure and temperature at the inlet and pressure drop across the orifice were measured respectively with a Bourdon gage, a thermocouple, and a well-type manometer. The manometer was filled with Meriam red oil having a specific gravity of 0.827 at 60°C. These measurements were used to determine the air flow rate using the following equation:

$$W_G = 134.0 \cdot KY \sqrt{\frac{(\Delta P_o) P_o}{T_o}} \quad (C-1)$$

where: W_G = air mass flow rate, lb/hr

K = orifice coefficient (velocity of approach correction included)

Y = compressibility correction

ΔP_o = pressure drop across the orifice, in. of oil

P_o = absolute pressure at the orifice inlet, psia

T_o = absolute temperature at the orifice inlet, $^{\circ}R$

This equation was obtained by combining Equations (112) and (114) on page 65 of the report of the ASME Research Committee on Fluid Meters (2), and making the following substitution and conversion:

D_o = orifice diameter = 0.500 in.

$$\Delta P_o = \frac{\text{pressure drop across orifice, in. of water}}{.827}$$

The orifice coefficient, K , was determined from the graph shown in Figure C.1. This graph gives K as a function of the pipe Reynolds number which can be calculated from the following equation:

$$(N_R)_p = 7.4 \frac{W_G}{\mu_G} \quad (C-2)$$

where μ_G is the air viscosity in $lb_m/ft \text{ hr}$. The air viscosity can be calculated from the following equation from the Nuclear Engineering Handbook (11):

$$\mu_G = \frac{0.0263 \left(\frac{T_o}{100} \right)^{3/2}}{\left(\frac{T_o}{100} \right) + 1.97} \quad lb_m/ft \text{ hr} \quad (C-3)$$

The values of K shown in Figure C.1 are based on a graphical interpolation of values reported in Table 12 of the report of the ASME Research Committee on Fluid Meters (2) for :

$$\beta = \frac{\text{orifice diameter}}{\text{pipe inside diameter}} = 0.242$$

The compressibility correction, Y , was determined from the following equation:

$$Y = 1 - 0.00874 \frac{\Delta P_o}{P_o} \quad (C-4)$$

This equation was derived from an equation given on page 170 of the

FIGURE C.1
ORIFICE COEFFICIENT (VELOCITY OF APPROACH INCLUDED)

report of the ASME Research Committee on Fluid Meters (2) using the following substitutions:

$$\beta = 0.242$$

$$k = \frac{\text{specific heat of air at constant pressure}}{\text{specific heat of air at constant volume}} = 1.4$$

It can be shown that, for the range of flow conditions used for the experiments described in this thesis, the values of K and Y are approximately:

$$K \approx 0.600$$

$$Y \approx 0.99$$

Thus, to a first approximation, Equation (C-1) can be written as follows:

$$W_G \approx 79.6 \sqrt{\frac{(\Delta P_o) P_o}{T_o}} \quad (C-5)$$

During the experiments, this equation was used to calculate the value of ΔP_o corresponding to a particular combination of W_G , P_o and T_o just before establishing a particular flow condition. In addition, as described in Appendix E, Section E.1, it is used to calculate the initial estimate of the air mass flow rate necessary to determine a value of K for use in Equation (C-1).

The accuracy and reproducibility of flow rates calculated using Equation (C-1) depends to a large extent on whether the orifice is properly located with respect to other flow disturbing elements in the hydraulic system. For the system described in this thesis, the nearest disturbing elements were: (1) a 90 degree elbow located about 26 diameters upstream and (2) a reducing coupling about 14

diameters downstream of the orifice plate. This arrangement was well within the recommendations given in the Chemical Engineers Handbook (28).

C.4.2 Apparatus for Measurement of Air Bleed Flow Rate

The air bleed flow rate from the air-water separation and water collection system was measured using a Fischer and Porter rotameter. The meter serial number was 6507A1124C1 and the tube number was B4-21-10. Two floats were provided. One was a no. BSX-497 float and the other was a no. BSVT-45 float. Both were made of stainless steel. The calibration curve for the no. BSX-497 float was obtained from the Fischer and Porter Co. and is shown in Figure C.2. The calibration curve and related data for the no. BSVT-45 float is shown in Figure C.3. The solid line in Figure C.3 is based on a personal communication with a representative of Fischer and Porter. The data points represent calibration measurements made by the author. Some were obtained by measuring, for a given rotameter reading, the volume of water displaced by the air flowing from the meter during a measured time interval for a given rotameter reading and a measured temperature and pressure. These measurements were carried out using the water supply and collection apparatus included in the hydraulic system. The other data points were obtained by calibrating the meter using water as the fluid and converting the data to scfm of air metered at 14.7 psia and 70°F using the following equation based on Equation (222) from page 87 of the report of the ASME Research Committee on Fluid Meters (2):

$$Q_G = Q_L \sqrt{\frac{P_L}{P_G}} \quad (C-6)$$

FIGURE C.2

CALIBRATION CURVE FOR ROTAMETER USED TO MEASURE AIR BLEED RATE

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FIGURE C.3
CALIBRATION CURVE FOR ROTAMETER USED TO MEASURE
AIR BLEED RATE

where: Q_G = air flow rate, scfm metered at 14.7 psia and 70°F

Q_L = water flow rate, cfm

ρ_L = water density, lb_m/ft³

ρ_G = air density at 14.7 psia and 70°F, lb_m/ft³

The calibration curves shown in Figures C.2 and C.3 provided a means of converting rotameter readings to cubic feet per minute of air metered at 14.7 psia and 70°F. However, since readings were usually taken at a different pressure and temperature, it was necessary to use the following equations to determine the air flow rate in actual or standard cubic feet per minute.

$$\left[Q_{G3}, \text{actual cfm metered at } T_3 \text{ and } P_3 \right] = \left[Q_{G3}, \text{scfm metered at 14.7 psia and 70°F} \right] \sqrt{\frac{(14.7) T_3}{P_3 (530)}} \quad (C-7)$$

$$\left[Q_{G3}, \text{scfm metered at } T_3 \text{ and } P_3 \right] = \left[Q_{G3}, \text{scfm metered at 14.7 psia and 70°F} \right] \sqrt{\frac{P_3 (530)}{(14.7) (T_3)}} \quad (C-8)$$

where: T_3 = absolute temperature at inlet to bleed rotameter, °R

P_3 = absolute pressure at inlet to bleed rotameter, psia

Equation (C-7) is derived from Equation (222) from page 87 of the report of the ASME Research Committee on Fluid Meters (2). Equation (C-8) results from the fact that:

$$\left[Q_{G3}, \text{scfm metered at } T_3 \text{ and } P_3 \right] = \left[Q_{G3}, \text{actual cfm metered at } T_3 \text{ and } P_3 \right] \sqrt{\frac{P_3 (530)}{(14.7) (T_3)}} \quad (C-9)$$

In addition to the Fischer and Porter rotameter, a smaller Brooks rotameter was also available. However, the range of air bleed rates was such that it was not necessary to use it.

C.4.3 Apparatus for Measurement of Water Flow Rate

The rate of water flow into the injection section was measured by means of a Type 1110, Size 8 Brooks rotameter. The serial number was 9416-1. The tube number was R-85-25-3. It was provided with two stainless steel floats. However, the range of water flow rates which were used was such that only the larger one was needed. The serial number of this float was 9416-1. The calibration curve is shown in Figure C.4. The data shown were obtained by determining, for a given rotameter reading, the volume of water flowing through the meter during a measured time interval. These calibration measurements were carried out using the water supply and collection apparatus in the hydraulic system.

C.4.4 Apparatus for Measurement of the Nitrogen Purge Flow Rate

The nitrogen purge flow rate to the pressure taps in the water injection and film removal sections of the vertical tube were indicated by a pair of identical Fischer and Porter rotameters. The model number of each meter was 10A3135M, the tube number was FP-1/4-20-P-3, and the float was a 1/4 in. GCD fiber glass sphere. Since the tube was calibrated in cubic centimeters of water per minute, Equations (C-6) and (C-7) were used to convert a particular rotameter reading to actual cubic feet of nitrogen per minute. On this basis, it was determined that a scale reading of 10 at the pressures and temperatures which were used for the experiments described in this thesis corresponded to a volumetric flow rate which was less than 0.1 percent of the lowest volumetric flow rate of air through the test section. Therefore, during the course of the experimental work, the purge rotameter readings were maintained at or below 10 on the meter scale and

FIGURE C.4
CALIBRATION CURVE FOR ROTAMETER USED TO MEASURE WATER
FLOW RATE

were not recorded.

C.5 Apparatus for Measurement of Pressure and Pressure Drop

Static pressure was measured at several locations in the hydraulic system by means of Bourdon gages. The gage used to measure the pressure at the exit of the bleed rotameter connected to the air-water separation and water collection apparatus was a Lonergan compound gage. The pressure side covered the range from 0 to 150 psig, with 1 psi subdivisions. The vacuum side covered the range from 0 to 30 in. Hg. The gages which were used to measure pressure: (1) upstream of the oil-free air orifice, (2) above the porous bronze in the water injection section, and (3) in the air supply pipe connected to the water supply tank were Lonergan pressure gages. Each gage covered the range from 0 to 160 psig, with 1 psi subdivisions. The gage used to measure the pressure in the water supply tank was an Ashcroft pressure gage covering the range from 0 to 150 psig with 2 psi subdivisions.

Each of the pressure gages were checked using a dead-weight gage tester. The Lonergan gages were checked at 5 psi intervals over their entire range. Within the range from 25 to 100 psig, they were found to be accurate within 0.5 psi. The Ashcroft gage was checked by comparison to one of the Lonergan gages and found to read from 0.5 to 1.5 psi high over the range from 10 to 120 psig.

The pressure drop across the air orifice was measured by means of a well-type, Model A-338A manometer. The serial number was 15835. It had a range of 61 in. and contained Meriam red oil with a specific gravity of 0.827.

The pressure drop between the water injection section and the film removal section was measured by means of a U tube manometer. The serial number was 386.93. It had a range of 36 in. and contained mercury. Another well-type manometer identical to the one described above, except that it contained distilled water, was also available. However, the range of values of the pressure drop was such that it was not necessary to use it.

C.6 Photographic Equipment

The motion pictures were taken with an Eastman Kodak, Type III, 16 mm. high speed camera driven by a universal motor. It was designed for continuous motion of the film at speeds up to 3000 frames/sec and utilized a rotating mechanical shutter which was optically designed so that the exposure was $1/5$ of the frame speed or a maximum of $1/15,000$ of a second. A Kodak Anastigmat $f/2.7$ 63 mm lens was used. Light was provided by three General Electric BFJ, 50,000 candle power flood lamps with integral reflectors. The film used was 16 mm Kodak Tri X Reversal for high speed cameras. This film had an ASA (tungsten) speed of 160.

The timer was a plastic pointer driven by a universal motor connected to a 110 volt, 60 cycle AC outlet through a Variac. The stroboscope used to measure the rotational speed of the timer is described in Section C.7 below.

The projector used to view the motion picture film after development was a Bell and Howell 173 BD Time and Motion Study Projector. It was equipped with a hand crank, frame counter, heat filter, and speed control. With the hand crank it was possible to project single frames as still pictures. The frame counter recorded the

number of frames advanced. It could be reset to any point and registered up to 10,000 frames and subtracted when the projector was run in reverse. The heat filter protected the film against damage during single frame projection. The speed control provided a speed range from 800 to 1500 pictures per minute.

C.7 Stroboscope

The stroboscope used to measure the rotational speed of the timer described in Section C.6 was a General Radio Co. Type 1531-A Strobotac. It could be used to measure speeds up to 250,000 rpm and had an accuracy of ± 1 percent after calibration.

This stroboscope was also the one used to make qualitative observations of the disturbance waves.

C.8 Air-Water Separators

Air-water separation was accomplished by means of Wright Austin, Type T, cyclone separators made of cast steel. The two separators connected to the top of the test section were provided with 1 in. pipe connections. At 90 psia, their capacity was approximately 150 scfm each. The two separators connected to the film removal section were provided with 1/2 in. pipe connections. At 90 psia, their capacity was approximately 55 scfm each. For the flow conditions used during the experimental work described in this thesis, the manufacturer stated that these separators were capable of removing from the air 99 per cent of all entrained water droplets with a diameter greater than 10 microns.

C.9 Water Supply and Collection Tanks

The water supply tank and the two water storage tanks had a capacity of 66 gallons and were made of galvanized steel. They were

designed for a maximum working pressure of 128.75 psig and were tested at 350 psig.

The two large collection tanks were made from approximately 5 ft long sections of 3 in. galvanized steel pipe. The small collection tank was made from an approximately 5 ft long section of 3/4 in. galvanized steel pipe. Thus, the large collection tanks had a capacity of approximately 2 gallons and the small tank had a capacity of approximately 0.2 gallons. Each tank was connected at each end to a sight glass through a tee, bushing, and a gage glass fitting. The glass tubes had an inside diameter of 1/2 in. The tanks were mounted on the rear of the panel board so that the three sight glass tubes were visible from the front. Meter sticks were mounted on the panel board next to each sight glass.

Each of the collection tanks was calibrated by measuring the volume of water corresponding to 1 in. changes in water level. This was done over the entire visible length of the sight glass using a graduated cylinder for the volumetric measurements. The results of these calibrations were as follows:

- 1) 3 in. collection tank connected to the air-water separators located downstream of the test section exit:

$$0.00449 \pm 0.00003 \text{ ft}^3/\text{in.}$$

$$0.0336 \pm 0.0002 \text{ gal/in.}$$

$$0.280 \pm 0.002 \text{ lb/in.}$$

- 2) 3 in. collection tank connected to the air-water separators connected to the film removal sections:

$$0.00447 \pm 0.00004 \text{ ft}^3/\text{in.}$$

$$0.0334 \pm 0.0003 \text{ gal/in.}$$

$$0.278 \pm 0.002 \text{ lb/in.}$$

3) 3/4 in. collection tank:

$$0.000399 \pm 0.000005 \text{ ft}^3/\text{in.}$$

$$0.00298 \pm 0.00004 \text{ gal/in.}$$

$$0.0249 \pm 0.0003 \text{ lb/in.}$$

where the lb/in. calibration assumes that $\rho_L = 62.3 \text{ lb/ft}^3$. The $\pm$ values are the standard deviations of the measurements made for fifty 1 in. intervals over the visible length.

C.10 Apparatus for Temperature Measurement

Air and water temperatures were measured by means of 30 ga. iron-constantan and 28 ga. chromel-alumel thermocouples. The hot junction of each thermocouple was protected by a well made from stainless steel tubing and a pipe plug or tube fitting installed in the hydraulic system. The cold junctions for each of the two types of thermocouples were also protected by wells made from stainless steel tubing. These wells were inserted through a cork stopper into a Thermos bottle filled with crushed ice and water.

All of the hot junctions and the two cold junctions were connected to a pair of rotary switches. These switches were used to match a particular hot junction with the appropriate cold junction and to connect the couple to a potentiometer. The potentiometer was a Leeds and Northrup no. 8691 portable millivolt potentiometer which was accurate to within $\pm 0.02 \text{ mv.}$

Each thermocouple was calibrated using as check points the temperature of: (1) a mixture of crushed ice and water, (2) water at an intermediate temperature measured with a mercury thermometer and

(3) boiling water. The calibrations were carried out with the hot and cold junctions in the stainless steel wells and with the couple connected to the potentiometer through the rotary switches. The results of this calibration indicated that each thermocouple was accurate to within $\pm 1^\circ\text{F}$ at each check point.

C.11 Test Section

Details of the design of the various sections of the test section are shown in Figures C.5 through C.9.

The purpose of the inlet section was to remove any swirl in the air stream which might have developed as result of upstream bends, etc. This was accomplished by providing a calming length of approximately 60 diameters and by installing straightening vanes at each end of the tube. These straightening vanes were made of 2 in. long sections of aluminum honeycomb with 1/8 in. hexagonal cells.

The porous bronze cylinders used in the water injection and film removal sections were specially made by Sintered Metals Inc. of Boston, Mass. The porosity and flow resistance of such materials is usually characterized by a permeability coefficient which is defined by Darcy's equation for flow through porous media which is given in the Chemical Engineer's Handbook (28).

$$\frac{\Delta P_b}{\Delta r} = \frac{1}{\alpha} \frac{\mu_L (v_{LS})_b}{g_c} \quad (C-10)$$

where: ΔP_b = pressure drop across the cylinder wall, lb_f/ft^2

Δr = thickness of the cylinder wall, ft

μ_L = water viscosity, $\text{lb}_m/\text{ft sec}$

SCALE 1:2

FIGURE C.5

DETAIL OF INLET SECTION

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FIGURE C.6

DETAILS OF WATER INJECTION SECTION

FIGURE C.7

DETAILS OF FILM REMOVAL SECTION

FIGURE C.8
DETAIL OF PLEXIGLAS SECTIONS

SCALE 1:2

DETAIL OF PLEXIGLAS SECTIONS

FIGURE C.9
 DETAILS OF STAINLESS STEEL SECTIONS

SCALE 1:2

$(V_{IS})_0$ = superficial water velocity (based on the total flow area provided by the cylinder wall), ft/sec

$$g_c = 32.17 \text{ lb}_m\text{ft}/\text{lb}_f \text{ sec}^2$$

α = the permeability coefficient, ft^2

The initial permeability coefficient of the porous bronze used in the water injection and film removal sections was determined experimentally and found to be approximately $2.6 \times 10^{-10} \text{ ft}^2$.

From Figures C.5 through C.9 it can be observed that the actual inside tube diameter varied from 0.494 in. to 0.500 in. However, the flanges were designed so that discontinuities at the joints would be negligible. A mean tube diameter of 0.497 in. was used for all calculations involving this quantity.

Details of the guide clamps used to provide vertical alignment of the tube are shown in Figure C.10. These clamps were machined from masonite. The larger section of each clamp was bolted to the aluminum channel support and lined up using a plumb line and level. Clamps were located at approximately 18 in. intervals along the length of the tube. Thus it was possible to align the tube to within 1/16 in. over its entire length.

C.12 Valves and Piping

The valve used to regulate the pressure of the air entering the test section was a 1 in. Crown no. RC 4100, pilot-controlled, pressure regulating valve. It was designed for a maximum primary pressure of 250 psig and an adjustable secondary pressure of 3 to 125 psig. The pilot valve was a 1/4 in. Crown no. R-2025 pressure regulating valve provided with air from the same compressors used to

FIGURE C.10

DETAILS OF TEST SECTION GUIDE CLAMPS

supply air to the water supply tank. The valve used to regulate the nitrogen pressure to the pressure tap purge system was a KGM, Model no. 1108 pressure regulating valve. It was designed for a maximum primary pressure of 2500 psig and adjustable secondary pressures from 0 to 200 psig.

The quick-acting valves used to direct water to collection or storage tanks were Jamesbury Type AllBB, double-seal, ball valves. These valves were installed in a section of $3/4$ in. pipe and provided essentially full $3/4$ in. pipe flow when opened. Only one-quarter turn was required to rotate the valve from full open to full closed position.

The valves used to regulate air and water flow rates were, respectively, $1/2$ in. and $3/8$ in. Lunkenheimer no. 73-PS, plug-seat, globe valves. The valves used to regulate the air bleed rate from the air-water separation and water collection system was a $1/4$ in. Hoke needle valve.

Piping in the oil-free air supply system was principally carbon steel, except for the section between the filter and the test section which was copper. Piping in the system providing air to the water supply tank was also carbon steel. All water system piping was galvanized steel except for the section between the second filter and the vertical tube, which was copper. Finally, all tubing used in the hydraulic system was made either of polyethelene or nylon-reinforced Tygon.

APPENDIX D

DETAILED EXPERIMENTAL PROCEDURES

D.1 General Procedure

The general procedure used to carry out the experimental work described in Chapter III was the following:

- 1) The various sections of the test section were arranged so that the film removal section or a Plexiglas section was located at the desired position.
- 2) If the pressure drop and the dispersed water fraction were to be measured, the axial distances from the center of the effective part of the porous bronze cylinder in the water injection section to the center of the effective part of the porous bronze cylinder in the film removal section and to the pressure tap in the film removal section were determined and recorded. An experimental condition was established using the procedure outlined in Section D.2 below. The pressure drop and dispersed water fraction were then measured using the procedure outlined in Section D.3.
- 3) If motion pictures were to be taken, the axial distance from the center of the effective part of the porous bronze cylinder in the water injection section to the center of the Plexiglas section to be photographed was determined and recorded. An experimental condition was established using the procedure outlined in Section D.2 below. Motion pictures were then taken according to the procedure outlined in Section D.4. After development, the motion picture films were analyzed to determine the frequency, velocity, and

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length of the disturbance waves as outlined in Section D.5.

- 4) For a particular test section arrangement, steps 2 and 3 were repeated for each of the experimental conditions.
- 5) The various sections of the test section were rearranged to locate the film removal section or a Plexiglas section at a new position, and steps 2 or 3 and 4 were repeated.
- 6) Step 5 was repeated until steps 2 or 3 and 4 had been carried out at the desired number of positions downstream of the water injection section.

D.2 Procedure Used to Establish a Flow Condition

For a particular arrangement of the test section, the following procedure was used to establish a flow condition:

- 1) The flow of air through the test section was started and the flow rate and inlet pressure were adjusted to their required values.
- 2) The inlet temperature of the air was adjusted to approximately 70°F by regulating the flow of city water through the air cooler.
- 3) The flow of water into the test section was started and the flow rate was adjusted to the required value.
- 4) The inlet temperature of the water was adjusted to approximately 70°F by regulating the flow of city water through the water cooler.
- 5) Data were recorded which could be used to determine the air mass flow rate, the water mass flow rate, the inlet pressure, and the inlet air and water temperature.

D.3 Procedure Used to Measure Pressure Drop and Dispersed Water Fraction

Once an experimental condition was established, the pressure drop and local dispersed water fraction were determined using the following procedure:

- 1) The nitrogen purge rate was adjusted to be the same for each of the two pressure taps. This rate was a negligible fraction of the air flow rate through the test section.
- 2) The pressure drop between the film removal section and the water injection section was measured and recorded.
- 3) The gate valve which isolates the test section from the air-water separation and water collection apparatus connected to the film removal section was opened and the air bleed rate to the atmosphere was increased until essentially all of the film was being removed through the porous bronze. This could be checked by visual inspection since the section of the tube just above the bronze was transparent. See Figure 3.8 in Chapter III.
- 4) The air and water mass flow rates, the inlet pressure, and the air and water inlet temperatures were adjusted as necessary.
- 5) Data were recorded which could be used to determine the air bleed rate from the air-water separation and water collection apparatus connected to the film removal section.
- 6) The water separated from the air-water mixture removed through the porous wall section was directed to one of the collection tanks. The rate of collection was determined by observing the change in the water level in this tank during a time interval measured with a stop watch.

- 7) Simultaneously, water separated from the air-water mixture leaving the top of the test section was directed to another collection tank. The rate of collection in this tank was also determined by observing the change in water level during a time interval measured with a stop watch.
- 8) In order to make certain that the film was being completely removed, steps 4 through 7 were repeated for a higher value of the air bleed rate.
- 9) Step 8 was repeated until the collection rates measured for at least three different air bleed rates were consistent to within 0.5 per cent of the total water flow rate. These measurements were then used to determine the dispersed water fraction as described in Appendix E, section E.1.

D.4 Procedure Used to Obtain Motion Pictures

For an experimental condition for which motion pictures were taken, the procedure used was the following:

- 1) The camera lens was adjusted and focused on the Plexiglas section to be photographed.
- 2) The camera was loaded with film and set to operate at its maximum speed of 3000 frames/sec.
- 3) The timer motor was started and its speed adjusted.
- 4) The timer speed was measured using a stroboscope.
- 5) The stroboscope was turned off and the flood lights were turned on.
- 6) The camera was started. After it stopped, the flood lights and timer were turned off.
- 7) The film was removed and stored for subsequent processing and analysis.

D.5 Procedure Used to Analyze the Motion Picture Films

After development, the motion picture films were analyzed by means of the projector described in Section C.6 of Appendix C. This projector could be used to run the film manually at slow speed or to study individual frames. For each roll of film, measurements were made of wave frequency, velocity, and disturbance length using the following procedure:

- 1) An 18 in. x 24 in. white card was marked with evenly spaced horizontal lines and mounted on a standard projection screen.
- 2) The roll of film to be analyzed was loaded into the projector.
- 3) The projector was started and approximately 25 ft of the 100 ft of film in the roll was allowed to run through it. This part of the roll was not analyzed since it was often overexposed or blurred as a result of the finite time required for the camera motor and rotating shutter to reach full speed.
- 4) The projector was stopped and the number indicated by the frame counter was noted.
- 5) The distance between the projector and the projection screen was adjusted until the spacing of the horizontal lines on the white card was equivalent to $1/8$ in. according to the scale mounted next to the Plexiglas section.
- 6) The projector lens was focused. The projector was started again and the remaining 75 ft of film in the roll were run through at slow speed or by hand. The number of disturbance waves passing the center of the Plexiglas section and the corresponding number

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of revolutions of the timer were counted and recorded. These measurements and the previously measured rotational speed of the timer were used to determine the average frequency of the disturbance waves during the observed time interval.

- 7) The projector was stopped before the end of the roll was reached and set for reverse motion. The film was then run backwards through the 75 ft of film analyzed in step 6. The projector was stopped when the frame counter indicated the number noted in step 4 and was reset for forward motion.
- 8) The last 75 ft of film were again run through the projection, this time entirely by hand. The length of the disturbance area and the distance traveled during approximately one or two revolutions of the timer were measured for each wave. The length of the disturbance area was measured when the wave was at the center of the Plexiglas section. The distance traveled during one or two rotations of the timer usually included 1 in. to 2 in. above and below the center of the Plexiglas section. These measurements, the measurements made in step 7, and the previously measured rotational speed of the timer were used to determine the average length of the wave disturbance area and the individual and average wave velocities as described in Appendix E, Section E.2.

APPENDIX E

COMPUTER PROGRAMS AND CALCULATION PROCEDURES

Two computer programs were written for the purpose of reducing the experimental data. Analysis and correlation of the reduced data and comparisons with data reported by Gill, et al. (12) and Cousins, et al. (8) were done partially by hand and partially by means of additional computer programs. These programs and hand calculation procedures are described in the following sections.

E.1 Computer Program for Reduction of Dispersed
Water Fraction and Pressure Drop Data

A flow diagram of the computer program used for reduction of dispersed water fraction and pressure drop data is shown in Figure E.1. The calculation procedure followed by this program is outlined below:

- 1) The first step is to read in and print the following calibration data which must be provided on the first 61 data cards.
 - a) Sixteen values of VIC and TIC. This is a table of values which can be used to convert iron-Constantan thermocouple readings to °F. VIC is the reading in millivolts and TIC is the corresponding temperature in °F. These data were obtained from the Handbook of Chemistry and Physics (19).
 - b) Six values of RE and OC which can be used to determine the orifice coefficient for a particular flow condition. RE is the air Reynolds number and OC is

FIGURE E.1

COMPUTER PROGRAM USED FOR REDUCTION OF DISPERSED WATER
FRACTION AND PRESSURE DROP DATA

the corresponding orifice coefficient from Figure C.1.

- c) Thirteen values of GPMI and GPMA which can be used to correct water flow rate data. GPMI is the indicated water flow rate in gpm and GPMA is the actual flow rate according to Figure C.4.
 - d) Sixteen values of VCA and TCA. This is a table of values which can be used to convert chromel-alumel thermocouple readings to °F.
 - e) Ten values of PCT and SCFM which can be used to convert data for air bleed rate from the air-water separation and water collection system to scfm. PCT is the scale reading in per cent and SCFM is the corresponding air flow rate in scfm of air at 14.7 psia and 70°F from Figure C.2.
- 2) Subroutine CONS is called. This subroutine is used to calculate the constant factors in the equations used for interpolation of the calibration data read in step 1. When interpolation is required later in the program an additional subroutine called SPLINE is used. This subroutine uses the calibration data required and the corresponding constants determined by CONS to carry out a spline fit interpolation. Both of these subroutines are described in detail by Pennington (27). Therefore, they will not be described further here.
- 3) The next data card should give the tube inside diameter, D, in inches. This card is read and D is printed.

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- 4) The next data card should give the run number, N , and the number of positions downstream of the water injection section, L , for which experimental data was obtained. This card is read and, if $N > 0$, the run number is printed and the program continues. If $N = 0$, the program exits.
- 5) The next data card should contain the values of $NPOS$, M , and $NFLOAT$. $NPOS$ is a number which identifies the position above the inlet corresponding to the next set of data cards. M indicates the number of data cards to be expected. $NFLOAT$ identifies the float used in the rotameter used to measure air bleed rate. This card is read and the value of $NPOS$ is printed.
- 6) The next data card should provide the following data for run N and position $NPOS$:
 - a) $FRSZ$, the distance from the center of the water injection section to the center of the film removal section, in.
 - b) PTZ , the distance from the center of the water injection section to the pressure tap in the film removal section, in.
 - c) PO , the pressure at the orifice inlet, psig.
 - d) TO , the temperature at the orifice inlet, mv.
 - e) DPO , the pressure drop across the orifice, in. of oil.
 - f) RL , the water rotameter reading, gpm.

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- g) P₁, the pressure at the tap located near the top of the water injection section, psig.
 - h) DP, the pressure drop between the pressure tap located near the top of the water injection section and the tap located near the top of the film removal section, in. Hg.
 - i) T_{G1}, the temperature of the air entering the test section, mv.
 - j) T_{L1}, the temperature of the water entering the test section, mv.
 - k) T₂, the temperature of the air leaving the separators located downstream of the test section, mv.
- 7) The following additional data should be provided on each of the next M-1 data cards:
- a) More values of T_{G1}, T_{L1}, and T₂, mv.
 - b) FDH, the observed change in water level in the collection tank connected to the air-water separators connected to the film removal section, in.
 - c) FDT, the time interval corresponding to FDH, min.
 - d) DDH, the observed change in water level in the collection tank connected to the air-water separators downstream of the test section, in.
 - e) DDT, the time interval corresponding to DDH, min.
 - f) R₃, the reading of the air bleed rotameter corresponding to FDH, FDT, DDH, and DDT, in per cent.
 - g) P₃, the pressure at the inlet to the air bleed rotameter, psig.

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- h) T3, the temperature at the inlet to the air bleed rotameter, mv.
- 8) The values of PO, TO, and DPO are used to calculate the air flow rate as follows:
- a) PO is converted to psia. TO is converted to °F using calibration data from step 1. Then TRY1 is calculated from PO, TO, and DPO using Equation (C-5).
 - b) RE is calculated from TRY1 and Equation (C-3).
 - c) RE is used to obtain a value of OC from the calibration data read in step 1.
 - d) TRY2 is calculated from PO, TO, DPO, and OC using Equations (C-1) and (C-4).
 - e) Steps c and d above are repeated to obtain AFLO, the air flow rate in lb_m/hr.
 - f) AFLO is substituted into the following equation to calculate QAIR, the air flow rate in scfm:

$$QAIR = \frac{AFLO}{(0.075)(60)} \quad (E-1)$$

where the constant, 0.075, is the density of air at 14.7 psia and 70°F in lb_m/ft³.

- g) Values of TRY1, TRY2, AFLO, and QAIR are printed out.
- 9) The values of RL and calibration data from step 1 are used to obtain GPMA, the actual water flow rate in gpm. This value is then substituted into the following equation to obtain WFLO, the water flow rate in lb_m/hr.

$$WFLO = 499.7 (GPMA) \quad (E-2)$$

and the result is printed out. The constant in this

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equation is based on a water density of $62.3 \text{ lb}_m/\text{ft}^3$.

- 10) The values of $TG1$, TLL , and $T2$ are converted to $^{\circ}\text{F}$ using calibration data from step 1. The results are printed out as $TEMPG1$, $TEMPLL$, and $TEMP2$. The average of all these temperatures is then calculated and printed out as $TEMP$.
- 11) The value of $P1$ is converted to psia and printed out as $PRESS1$. The value of DP is converted to psi and printed out as $DPRESS$.
- 12) The first set of values of FDH , FDT , DDH , DDT , $R3$, $P3$ and $T3$ is used to carry out the following calculations:
 - a) FDH , FDT , DDH and DDT are substituted into the following equations to obtain values of FCR and DCR :

$$FCR = 16.68 \frac{FDH}{FDT} \quad (E-3)$$

$$DCR = 16.80 \frac{DDH}{DDT} \quad (E-4)$$

FCR is the collection rate in lb_m/hr from the separators connected to the film removal section and DCR is the collection rate in lb_m/hr from the separators downstream of the test section. The constant factors are based on the results of the calibrations of the collection tanks given in Appendix C, Section C.8.

- b) FCR and DCR are added to obtain a value of the total collection rate, TCR .

- c) The percent difference between TCR and the value of WFLO from step 9 is calculated as follows:

$$\text{CHECK} = \frac{(\text{TCR} - \text{WFLO})}{\text{WFLO}} (100) \quad (\text{E-5})$$

- d) A value of the ratio of DCR to TCR is calculated. This quantity is called DRATIO.
- e) P3 is converted to psia. T3 is converted to °F using calibration data from step 1. R3 is used to obtain a value of Q3, the air bleed rate in scfm metered at 14.7 psia and 70°F. If the value of NFLOAT in step 5 was zero, Q3 is obtained using calibration data from step 1. If NFLOAT is 1, Q3 is obtained from the following equation based on a personal communication with a representative of the Fischer and Porter Co. (see Figure C.3):

$$Q3 = 0.0247 (R3) \quad (\text{E-6})$$

- f) The results from step 12e are substituted into Equation (C-8) to obtain a value of Q3TOT, in scfm metered at T3 and P3.
- g) The values of Q3TOT, FCR, T3, and P3 are substituted into the following equation to calculate Q3TS, the net rate of air removal from the test section:

$$Q3TS = Q3TOT - \frac{\text{FCR} (P3) (530)}{3738 (14.7) (T3)} \quad (\text{E-7})$$

This equation gives Q3TS in scfm metered at P3 and T3.

h) A value of the ratio of Q3TS to QAIR is calculated.

This quantity is called QRATIO.

13) Step 12 is repeated for the remaining set of values of FDH, FDT, DDH, DDT, R3, P3, and T3.

14) The M values of FCR, DCR, TCR, CHECK, DRATIO, Q3TOT, Q3TS, and QRATIO are printed out.

15) The dispersed water fraction, DFRACT, is determined as follows:

a) The various values of DRATIO from steps 12 and 13 are tested to determine which ones are within 0.005 of the value corresponding to the largest value of Q3TS. The value of 0.005 was selected because it was found that values of DRATIO obtained for a particular value of Q3TS were always reproducible within this limit.

b) Subroutine LSTSQR is used to carry out a linear least square fit to the values of DRATIO which satisfied the preceding test. This subroutine is described in detail by Pennington (27). Therefore, it will not be described here.

c) The results of step 15b are used to obtain the value of DRATIO corresponding to Q3TS = 0. This value is considered to be the dispersed water fraction, DFRACT. The value of DFRACT is printed out.

16) Steps 5 through 15 are repeated until they have been carried out for each of the L positions corresponding

to run N.

- 17) If L is less than 7 the program returns to step 4.
(This test was included so that the remaining steps could be skipped in the case of partial runs made to check reproducibility, etc.) If L is greater than 7 the program proceeds to step 18.
- 18) The values of AFLO, WFLO, PRESS1 and TEMP obtained from the data for each of the L positions are used to obtain the average values of these quantities. These averages are called AFLOA, WFLOA, PINA, and TEMPA.
- 19) The values DFRACT and DPRESS obtained in steps 5 through 16 are substituted into the following equations to obtain the corresponding values of DFLO and PRESSZ:
- $$DFLO = DFRACT(WFLOA) \quad (E-8)$$
- $$PRESSZ = PINA - DPRESS \quad (E-9)$$
- DFLO is the dispersed water flow rate in lb_m/hr . PRESSZ is the local pressure in psia.
- 20) The values of AFLOA, WFLOA, TEMPA, PTZO, PINA, PTZ, PRESSZ, FRSZ, and DFLO are printed out and punched on cards. (PTZO is the distance between the center of the water injection section and the inlet pressure tap. The value of this quantity is given on a card included in the Fortran deck.)
- 21) The program returns to step 4.

E.2 Computer Program for Reduction of Data from the Motion Pictures

The flow diagram of the computer program used for reduction of the data obtained from motion pictures is shown in Figure E.2. The

FIGURE E. 2
COMPUTER PROGRAM USED FOR REDUCTION OF DATA FROM
THE MOTION PICTURES

procedure followed by this program is outlined below:

- 1) The first step is to read in a data card which gives the run number, N , and the number of positions downstream of the water injection section for which experimental data was obtained, L . (The run number, N , for a particular condition is the same as the run number used for this condition for the program used to reduce dispersed water fraction and pressure drop data. For this reason it is not necessary to again read in and reduce data related to the calculation of air mass flow rate, water mass flow rate, etc.) If N is > 0 , it is printed out and the program continues. If $N = 0$ the program exits.
- 2) The next data card should contain the values of $NPOS$ and M . $NPOS$ is a number which identifies the position above the inlet corresponding to the next set of data cards. M indicates the number of data cards to be expected in step 4 below. $NPOS$ is printed out.
- 3) The next card should provide the following data for run N and position $NPOS$.
 - a) $PHOTOZ$, the distance from the center of the water injection section to the center of the Plexiglas section, in.
 - b) $NCOUNT$, the number of waves counted during the observed interval.
 - c) $REVN$, the number of revolutions of the timer during the observed interval.
 - d) RPM , the rotational speed of the timer, rpm.

This card is read in.

- 4) The next M cards must each contain the following data concerning a wave:
- a) WAVEL, the disturbance length of the wave in inches.
 - b) DREV, the number of revolutions of the timer corresponding to the observed movement of the wave.
 - c) DZ, the distance traveled by the wave in inches.

These data and the data read in step 3 are printed out.

The number waves measured, M, is also printed out.

- 5) The data read in steps 3 and 4 are used to calculate several quantities as follows:

- a) The wave frequency in waves per second is calculated from the equation:

$$\text{FREQ} = \frac{(\text{NCOUNT}) (\text{RPM})}{60 (\text{REVN})} \quad (\text{E-10})$$

- b) The standard deviation of the wave frequency is calculated from the equation:

$$\text{SDFREQ} = \frac{\text{NCOUNT} (\text{RPM})}{60 (\text{REVN})} \quad (\text{E-11})$$

(The use of this equation assumes that, to a first approximation, the frequency distribution which describes the formation of waves is a Poisson type of distribution. For such a distribution the standard deviation of the number of waves observed in a given time interval would be equal to the square root of this number.)

- c) The average wave disturbance length, AWAVEL, is

determined by calculating the sum of the M values of WAVEL and then dividing by M.

- d) The standard deviation of the distribution of values of wave length about the average value is calculated from the following equation:

$$SDWL = \sqrt{\frac{1}{(M-1)} \sum_{J=1}^{J=M} [WAVEL(J) - AWAVEL]^2} \quad (E-12)$$

- e) Individual values of wave velocity in ft/sec are calculated from values of DZ and DREV using the equation:

$$WAVEV = \frac{(RPM) (DZ)}{(720) (DREV)} \quad (E-13)$$

- f) The average wave velocity, AWAVEV, is then determined by calculating the sum of the M values of WAVEV from the preceding step and dividing by M.
- g) The standard deviation of the distribution of values of wave velocity about the mean value is calculated from the following equation:

$$SDWV = \sqrt{\frac{1}{(M-1)} \sum_{J=1}^{J=M} [WAVEV(J) - AWAVEV]^2} \quad (E-14)$$

- h) The average fraction of the film surface covered by disturbance waves, SURFN, is calculated from the following equation:

$$SURFN = \frac{(FREQ) (AWAVEL)}{(AWAVEV) (12)} \quad (E-15)$$

E-15

- i) The standard deviation of the average fraction of the surface covered by disturbance waves is calculated from the following equation:

$$SDSN = SURFN \sqrt{\left(\frac{SDFREQ}{FREQ}\right)^2 + \frac{1}{M} \left[\left(\frac{SDWL}{AWAVEL}\right)^2 + \left(\frac{SDWV}{AWAVEV}\right)^2 \right]} \quad (E-16)$$

- 6) The value of PHOTOZ and the values of FREQ, SDFREQ, AWAVEL, SDWV, SURFN, and SDSN are printed out.
- 7) The frequency distribution for wave length is determined using the following procedure:
 - a) The range of possible values of WAVEL extending from 1/16 to 2-1/16 in. is divided into 16 equal intervals.
 - b) Each of the values of WAVEL read in step 4 are then tested and the number of values of WAVEL which fall within each interval is determined.
- 8) The number of values of WAVEL found to be within each of the 16 tested intervals is printed out.
- 9) The frequency distribution for wave velocity is determined in the same manner as the frequency distribution for wave disturbance length. In this case the intervals are determined by dividing the range of possible values of WAVEV extending from 8.125 ft/sec to 29.375 ft/sec into 16 equal intervals.
- 10) The number of values of WAVEV found to be within each of the 16 tested intervals is printed out.
- 11) Steps 2 through 10 are repeated until they have been carried out for each of the L positions corresponding

to run N.

- 12) The program returns to step 1.

E.3 Calculation Procedures and Computer Program Used for Data Analysis

Values of $B_4(Z)$ for a particular flow condition were calculated by hand from values of WFLOA and SURFN using Equation (5-17). The results of this calculation are shown graphically in Figure 5.6.

A computer program was used to calculate: (1) values of the left member of Equation (5-21), (2) quantities which can be used to check some of the assumptions made in Section 5.2 of Chapter V, and (3) values of the dimensionless quantities defined by Equations (6-1), (6-4), and (6-7). The flow diagram for this program is shown in Figure E.3. The calculation procedure is outlined below:

- 1) Values of N and L are read in. These quantities are defined as for the program described in Section E.1. If $N > 0$, the run number is printed out and the program continues. If $N = 0$, the program exits.
- 2) The values of D, AFLOA, WFLOA, TEMPA, PTZO, and PINA for run N are read from the cards punched by the computer program described in section E.1. However, in the program described in this section, AFLOA is referred to as AFLO, WFLOA is referred to as WFLO, TEMPA is referred to as TEMP, PTZO is referred to as PTZI, and PINA is referred to as PI.
- 3) L cards containing values of PTZ, PRESSZ, FRSZ, and DFLO are read in. These cards are also from those punched by the program described in section E.1. However, in the

FIGURE E.3

COMPUTER PROGRAM USED FOR DATA ANALYSIS

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program described in this section, PRESSZ is referred to as PRESS.

- 4) Values of D, AFLO, WFLO, TEMP, and PI are printed out.
- 5) L intermediate values of ZI are determined using:

$$ZI(1) = \frac{FRSZ(1)}{2} \quad (E-17)$$

for I=1, and

$$ZI(I) = \frac{FRSZ(I) + FRSZ(I+1)}{2} \quad (E-18)$$

for I=2 through L.

- 6) Intermediate values of pressure are next determined for each value of ZI. These values are given the symbol, P, and are determined from the values of PTZI and PI read in step 2 and the L values of PTZ and PRESS read in step 3. This is done using subroutines SPLINE and CONS which accomplish a spline fit interpolation as described in Section E.1.
- 7) Intermediate values of the mass flow rate of dispersed water, WD, corresponding to each value of ZI are determined from the L values of DFLO and FRSZ. This was also done using subroutines SPLINE and CONS.
- 8) Intermediate values of pressure are also determined for each value of FRSZ. These values are given the symbol, PRESI.
- 9) Values of the rate of change of the mass flow rate of dispersed water with respect to distance along the tube are determined from the L values of FRSZ and DFLO

E-19

using:

$$DWD(I) = \left[\frac{DFLO(1)}{FRSZ(1)} \right] \quad (12) \quad (E-19)$$

for I=1,

$$DWD(I) = \left[\frac{DFLO(I)-DFLO(I-1)}{FRSZ(I)-FRSZ(I-1)} \right] \quad (12) \quad (E-20)$$

for I from 2 through 5, and

$$DWD(I) = \left[\frac{DFLO(I)-DFLO(5)}{FRSZ(I)-FRSZ(5)} \right] \quad (12) \quad (E-21)$$

for I from 6 through L. The values of DWD(I) for I from 6 through L are then replaced by their average value.

(The latter procedure was based on the observation that the rate of change of the mass flow rate of dispersed water with distance along the tube was essentially constant for values of FRSZ greater than FRSZ(5).) The values of DWD(I) obtained from this step have the units, lb/hr ft, and are associated with the corresponding values of ZI calculated in step 5.

- 10) Values of the pressure gradient, DP, are determined from the values of PRESI determined in step 8 and the corresponding values of FRSZ. This is done using

$$DP(I) = \left[\frac{PRESI(1)-PI}{FRSZ(1)} \right] \quad (114) \quad (E-22)$$

for I=1,

$$DP(I) = \left[\frac{PRESI(I-1)-PRESI(I)}{FRSZ(I)-FRSZ(I-1)} \right] \quad (114) \quad (E-23)$$

for I from 2 through 3, and

E-20

$$DP(I) = \frac{FRESI(3) - PRESS(I)}{FRSZ(I) - FRSZ(3)} \quad (E-24)$$

for I from 4 through L. The values of DP(I) for I from 4 through L are then replaced by their average value.

(The latter procedure was based on the observation that the pressure gradient was essentially constant for values of FRSZ greater than FRSZ(3).) The values of DP obtained from this step have the units, lb_f/ft^3 , and are associated with the values of ZI calculated in step 5.

- 11) The L values of ZI, WD, DWD, P, and DP obtained from the preceding calculations are printed out.
- 12) Next, a table of values of FYPLUS vs. YPLUS are calculated using the following equations:

$$FYPLUS = 0.5 (YPLUS)^2 \quad (E-25)$$

for $YPLUS < 5$,

$$FYPLUS = 12.5 - 8.05 (YPLUS) + 5.0 (YPLUS) \ln(YPLUS) \quad (E-26)$$

for $5 < YPLUS < 30$

$$FYPLUS = 3.0 (YPLUS) + 2.5 (YPLUS) \ln(YPLUS) - 64.0 \quad (E-27)$$

for $YPLUS > 30$

The quantity, FYPLUS is defined as follows:

$$FYPLUS = \frac{(WFLM) (12)}{(\pi) (D) (2.375)} \quad (E-28)$$

where WFLM is the film flow rate calculated from:

$$WFLM = WFLOA - WD \quad (E-29)$$

E-21

D is the tube diameter in feet, and the constant, 2.375, is the viscosity of water at 70°F in lb_m/ft hr. Thus, FYPLUS is dimensionless and is equivalent to a film Reynolds number (see Equation (6-7) of Chapter VI). The quantity, YPLUS, is given by the following equation:

$$YPLUS = \frac{DELTA}{12.0} \left\{ \sqrt{\frac{(TAUW) (32.2)}{(62.3)}} \left[\frac{(62.3) (3600)}{(2.375)} \right] \right\} \quad (E-30)$$

where DELTA is the water film thickness in inches, TAUW is the wall shear stress in lb_f/ft². The constant, 62.3, is the density of water at 70°F in lb_m/ft³. The constant, 2.375, is as defined above. Other constants are as necessary to make YPLUS dimensionless. Equations (E-25), (E-26), and (E-27) were derived by Levy (24). This derivation involved the integration of a generalized velocity profile for the water film based on the following assumptions: (1) the shear stress in the film is constant and equal to the shear stress at the wall, (2) the mixing length distribution in the film is the same as for single-phase flow and (3) the gravitational forces are negligible with respect to shear forces. The details will not be repeated here.

13) L values of RHOG, CONC, RHOC, and VGS are calculated as follows:

a) Values of the air density, RHOG, are calculated using the following equation:

$$RHOG = \frac{P}{196.0} \quad (E-31)$$

E-22

The units of RHOG are lb_m/ft^3 .

- b) Values of the concentration of water in the dispersed phase, CONC, are calculated using the following equation:

$$\text{CONC} = \frac{(\text{WD}) (\text{RHOG})}{\text{AFLO}} \quad (\text{E-32})$$

The units of CONC are lb_m/ft^3 .

- c) Values of the average density of the dispersed phase, RHOC, are calculated from the following equation:

$$\text{RHOC} = \left[\frac{(1-\text{XC})}{62.3} + \frac{\text{XC}}{\text{RHOG}} \right] \quad (\text{E-33})$$

where XC is the quality in the dispersed phase calculated using the following equation:

$$\text{XC} = \frac{\text{AFLO}}{\text{WD} + \text{AFLO}} \quad (\text{E-34})$$

The units of RHOC are lb_m/ft^3 .

- d) Values of the superficial air velocity, VGS, are calculated using the following equation:

$$\text{VGS} = \frac{(\text{AFLO}) (196) (144)}{P (A) (3600)} \quad (\text{E-35})$$

where A is the cross sectional area of the tube in in^2 . The units of VGS are ft/sec .

- 14) Values of DPF, the frictional component of the total pressure gradient, are calculated as follows:

- a) L values of DPAGI, the component of the total pressure gradient due to acceleration of the air, are

E-23

calculated using the following equation:

$$DPAGI = \frac{(VGS)^2 (DP)}{(32.2) (196) (144)} \quad (E-36)$$

- b) L values of DPADI, the component of the total pressure gradient due to the acceleration of the dispersed water, are calculated using the following equation:

$$DPADI = \frac{(VGS) (DWD) (144)}{(A) (32.2) (3600)} + \frac{(WD) (VGS) (DP)}{(P) (A) (32.2) (3600)} \quad (E-37)$$

- c) L values of DPF are calculated from:

$$DPF = DP - DPAGI - DPADI \quad (E-38)$$

These equations were derived from conservation of momentum, assuming that gravitational effects are negligible and that the dispersed phase occupies the entire cross section of the tube. The units of DPF, etc. are lb_f/ft^3 .

- 15) L values of the shear stress at the tube wall, τ_{uw} , are calculated using the equation:

$$\tau_{uw} = \frac{(DPF) (D)}{(48)} \quad (E-39)$$

- 16) L values of FYPLUS are calculated using Equations (E-28) and (E-29).

- 17) L values of YPLUS corresponding to each of the values of FYPLUS are determined from the table of values of these quantities calculated in step 12. This is done by means

E-24

of the spline fit interpolation subroutines, SPLINE and CONS (see Section E.1)

- 18) L values of the film thickness, DELTA are calculated from Equation (E-30) using the values of TAUW determined in step 15 and values of YPLUS determined in step 17.

- 19) Values of the cross sectional area of the dispersed phase, AC, and the cross sectional area of the film, AF, are calculated from the values of DELTA using the following equations:

$$AC = (0.785) DC^2 \quad (E-40)$$

$$AF_{LM} = \left(\frac{A}{114} \right) - AC \quad (E-41)$$

where

$$DC = \left[\frac{\bar{D} - (2) (DELTA)}{12} \right] \quad (E-42)$$

- 20) L values of the void fraction, VOID, are calculated from the equation:

$$VOID = \frac{AC}{A} \quad (E-43)$$

- 21) L values of the average velocity of the dispersed phase, the average velocity of the film, and the difference between the average velocity of the dispersed phase and the film are next calculated from the equation:

$$VC = \left[1 - \frac{(WD) (RHOG)}{62.3 (AFLO)} \right] \frac{VGS}{VOID} \quad (E-44)$$

E-25

$$VFLM = \frac{(WFLO - WD)}{(AFLM) (62.3) (3600)} \quad (E-45)$$

$$DV = (VC - VFLM) \quad (E-46)$$

The units of VC, VFLM, and DV are ft/sec.

22) L values of DPF are recalculated as follows:

a) L values of DPAG are calculated from the equation:

$$DPAG = DPAGI \left[\frac{VC}{VGS} \right]^2 \quad (E-47)$$

b) L values of DPAD are calculated from the equation:

$$DPAD = DPADI \left[\frac{VC}{(VGS) (VOID)} \right] \quad (E-48)$$

c) L values of DPG, the component of the total pressure gradient due to gravity, are calculated from the equation:

$$DPG = \left[(RHOC) (VOID) \right] + \left[(62.3) (1 - VOID) \right] \quad (E-49)$$

d) L values of DPF are calculated from:

$$DPF = DP - DPAG - DPAD - DPG \quad (E-50)$$

The units of DPF, etc. are lb_f/ft^3 .

23) L values of TAUW are recalculated using Equation (E-39).

24) Steps 18 through 23 are repeated twice more with the values of TAUW determined in step 23.

25) L values of the interfacial shear stress are calculated from the following equation:

$$TAUI = \left[DP - DPAG - DPAD - RHOC \right] \frac{DC}{4} \quad (E-51)$$

26) Approximate values of the interfacial shear stress are

E-26

calculated from the equation:

$$\text{TAUA} = (\text{DP}) \frac{\text{DC}}{4} \quad (\text{E-52})$$

27) The values of ZI and the corresponding values of several of the quantities calculated in steps 13 through 26 are printed out.

28) L values of the dimensionless quantities defined by Equations (6-1) and (6-4) are calculated using the following equations:

$$\text{DPOG} = \frac{\text{DP}}{62.3} \quad (\text{E-53})$$

$$\text{DPOST} = \frac{(\text{DP}) (\text{D}^2)}{(8) (0.00498) (144)} \quad (\text{E-54})$$

29) Values of ZI and corresponding values of DPOG and DPOST are printed out. Values of FYPLUS are also printed out. The latter quantities are given the symbol RNFLM since they are also values of the film Reynolds number.

30) L values of the left side of Equation (5-21) are calculated using the following equation:

$$\text{CORQ} = \frac{(\text{DWD}) (\text{P}) (144)}{(\text{DP}) (\text{AFLO}) (\text{WFLO})^{0.5}} \quad (\text{E-55})$$

31) L values of the following ratios are calculated:

$$\text{RV} = \frac{\text{VC}}{\text{DV}} \quad (\text{E-56})$$

$$\text{RTAU} = \frac{\text{TAUA}}{\text{TAUI}} \quad (\text{E-57})$$

E-27

- 32) Values of ZI and the corresponding values of CORQ, RV, and RTAU are printed out.
- 33) The program returns to step 1.

E.4 Calculation Procedure and Computer Programs Used for Data Correlation

Average values of the left side of Equation (5-21) were calculated by hand from the values of CORQ obtained from the computer program described in Section E.3. This calculation was limited to those experimental conditions for which motion pictures were obtained. The resulting values were plotted on Figure 5.7. This graph was then used to determine the constants which appear in Equation (5-24).

Equation (5-24) was integrated to obtain the expression in the bracket of Equation (5-25). Then, values of this expression were calculated by hand for each value of FRSZ for which values of DFLO and PRESS were determined as described in Section E.1. The results of this calculation were punched on IBM cards.

The IBM cards containing the values of the expression in the bracket of Equation (5-25) and the cards punched by the program described in Section E.1 were used as the input to a short computer program. The values of the expression in the bracket of Equation (5-25) were given the symbol FZOD. The program calculated values of the dispersed water fraction from the experimental data and from Equation (5-25). These results were given the symbols: Q and QPP, respectively. A flow diagram of the program is shown in Figure E.4.

Finally, values of the dispersed water fraction corresponding to the flow conditions used by Gill, et al. (12) and Cousins, et al. (8) were also calculated by means of short computer programs.

FIGURE E. 4
COMPUTER PROGRAM USED FOR DATA CORRELATION

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However, except for the fact that values of the dispersed water fraction were calculated from Equation (6-9) instead of Equation (5-25), these programs were essentially the same as the one shown in Figure E.4.

APPENDIX F

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TABULATED RESULTS

The principal results obtained using the computer programs described in Sections E.1 and E.2 of Appendix E are tabulated in Tables F.1, F.2, and F.3 which follow.

LE F.1

OF DISPERSED WATER FRACTION

DISPERSED WATER FRACTION, w_d/w_L						
9.25 in.	Z=41.25 in.	Z=59.25 in.	Z=82.75 in.	Z=106.75 in.	Z=124.25 in.	Z=130.25 in.
0.011	0.012	0.014	0.015	0.016	0.016	0.017
0.020	0.021	0.022	0.024	0.025	0.026	0.027
0.025	0.028	0.031	0.034	0.035	0.034	
0.032	0.038	0.043	0.046	0.048	0.050	0.054
0.043	0.049	0.054	0.057	0.058	0.060	0.062
0.051	0.054	0.057	0.061	0.063	0.065	
0.054	0.057	0.059	0.067	0.065	0.070	0.071
0.058	0.062	0.064	0.068	0.071	0.073	0.076
0.080	0.102	0.118	0.131	0.135	0.142	0.141
0.099	0.111	0.124	0.133	0.137	0.146	0.145
0.101	0.111	0.123	0.130	0.134	0.145	0.143
0.099	0.107	0.118	0.129	0.134	0.145	0.145
0.100	0.108	0.117	0.126	0.132	0.141	0.145
0.153	0.190	0.225	0.247	0.262	0.276	0.282
0.170	0.198	0.225	0.250	0.267	0.290	0.288
0.165	0.190	0.212	0.237	0.258	0.278	0.280
0.155	0.173	0.196	0.222	0.249	0.274	0.277
0.151	0.169	0.192	0.217	0.241	0.261	
0.227	0.277	0.323	0.359	0.384	0.400	0.405
0.240	0.283	0.331	0.375	0.412	0.445	0.447
0.230	0.266	0.309	0.360	0.401	0.444	0.453
0.213	0.248	0.291	0.345	0.393		
0.143	0.166	0.191	0.225	0.242	0.265	0.262
0.078	0.087	0.096	0.106	0.108	0.115	0.114
0.198	0.236	0.272	0.328	0.354	0.384	0.389
0.158	0.187	0.212	0.247	0.264	0.281	0.283
0.117	0.133	0.150	0.167	0.171	0.183	

TABLE F.1

RESULTS OF MEASUREMENTS OF DISPERSED WA

Flow Condition Number	Air Flow Rate W_G , lb _m /hr	Water Flow Rate W_L , lb _m /hr	Inlet Pressure P_1 , psia				
				Z=5.75 in.	Z=17.75 in.	Z=29.25 in.	Z=41
1	51	102	90	0.003	0.008	0.011	0
2	51	199	90	0.010	0.016	0.020	0
3	51	299	90	0.015	0.022	0.025	0
4	101	102	90	0.003	0.022	0.032	0
5	101	199	90	0.015	0.034	0.043	0
6	101	299	90	0.026	0.043	0.051	0
7	101	411	90	0.036	0.047	0.054	0
8	101	524	90	0.043	0.051	0.058	0
9	151	102	90	0.008	0.053	0.080	0
10	151	199	90	0.026	0.074	0.099	0
11	151	299	90	0.041	0.080	0.101	0
12	151	411	90	0.053	0.082	0.099	0
13	151	524	90	0.051	0.086	0.100	0
14	201	102	90	0.018	0.098	0.153	0
15	201	199	90	0.042	0.124	0.170	0
16	201	299	90	0.057	0.127	0.165	0
17	201	411	90	0.068	0.124	0.155	0
18	201	524	90	0.076	0.124	0.151	0
19	251	102	90	0.034	0.149	0.227	0
20	251	199	90	0.060	0.174	0.240	0
21	251	299	90	0.078	0.174	0.230	0
22	251	411	90	0.088	0.170	0.213	0
23	101	199	40	0.038	0.106	0.143	0
24	101	199	60	0.023	0.060	0.078	0
25	151	199	55	0.049	0.143	0.198	0
26	151	199	65	0.039	0.116	0.158	0
27	151	199	80	0.030	0.086	0.117	0

Notes: (1) The quantity, Z, is the distance from the water injection section to the film removal section.

(2) Tube Diameter, D=0.497 in.

(3) Inlet Temperature, t_1 =70°F.

BLE F.2

ELEMENTS OF PRESSURE DROP

TOTAL PRESSURE DROP, ΔP , psi.							
n.	Z=32.00 in.	Z=44.00 in.	Z=62.00 in.	Z=85.50 in.	Z=109.50 in.	Z=127.00 in.	Z=133.00 in.
	0.32	0.47	0.64	0.91	1.18	1.37	1.40
	0.49	0.69	0.98	1.45	1.82	2.09	2.16
	0.66	0.93	1.30	1.87	2.41	2.75	
	0.66	0.93	1.33	1.87	2.38	2.77	3.00
	1.01	1.37	1.96	2.75	3.54	4.08	4.30
	1.30	1.79	2.53	3.54	4.54	5.23	
	1.57	2.18	3.07	4.35	5.54	6.38	6.73
	1.82	2.50	3.54	4.96	6.40	7.41	7.71
	1.15	1.57	2.23	3.16	4.00	4.57	4.74
	1.64	2.26	3.17	4.49	5.72	6.48	6.80
	2.04	2.82	4.00	5.62	7.12	8.20	8.59
	2.43	3.34	4.74	6.70	8.54	9.84	10.26
	2.65	3.78	5.40	7.56	9.67	11.32	11.83
	1.72	2.33	3.31	4.57	5.89	6.80	7.07
	2.38	3.24	4.57	6.33	8.10	9.33	9.67
	2.92	3.98	5.65	7.83	10.04	11.59	11.96
	3.41	4.66	6.65	9.21	11.86	13.72	14.19
	3.73	5.20	7.49	10.31	13.36	15.49	
	2.36	3.19	4.47	6.14	7.86	9.08	9.44
	3.17	4.30	6.01	8.30	10.61	12.18	12.78
	3.85	5.23	7.41	10.24	13.04	15.02	15.81
	4.39	6.11	8.69	12.05	15.42		
	1.89	2.60	3.66	5.13	6.60	7.68	8.00
	1.35	1.87	2.68	3.71	4.84	5.60	5.89
	2.43	3.39	4.74	6.53	8.35	9.67	10.07
	2.11	2.97	4.15	5.77	7.36	8.47	8.86
	1.79	2.48	3.51	4.89	6.24	7.24	

TABLE F.2

RESULTS OF MEASUREMENTS OF PRESSURE

Flow Condition Number	Air Flow Rate W_G , lb _m /hr	Water Flow Rate W_L , lb _m /hr	Inlet Pressure P_1 , psia	TO			
				Z=2.75 in.	Z=8.50 in.	Z=20.50 in.	Z=32.00 in.
1	51	102	90	0.00	0.07	0.21	0.32
2	51	199	90	0.00	0.10	0.32	0.49
3	51	299	90	0.00	0.15	0.44	0.66
4	101	102	90	0.00	0.15	0.42	0.66
5	101	199	90	0.00	0.22	0.64	1.01
6	101	299	90	0.00	0.29	0.83	1.30
7	101	411	90	0.00	0.37	1.01	1.57
8	101	524	90	0.00	0.41	1.15	1.82
9	151	102	90	0.00	0.25	0.74	1.15
10	151	199	90	0.00	0.37	1.06	1.64
11	151	299	90	0.00	0.47	1.33	2.04
12	151	411	90	0.00	0.54	1.55	2.43
13	151	524	90	0.00	0.61	1.72	2.65
14	201	102	90	0.00	0.37	1.08	1.72
15	201	199	90	0.00	0.52	1.52	2.38
16	201	299	90	0.00	0.64	1.87	2.92
17	201	411	90	0.00	0.76	2.16	3.41
18	201	524	90	0.00	0.83	2.41	3.73
19	251	102	90	0.00	0.52	1.47	2.36
20	251	199	90	0.00	0.71	1.96	3.17
21	251	299	90	0.00	0.88	2.43	3.85
22	251	411	90	0.00	0.98	2.82	4.39
23	101	199	40	0.00	0.42	1.20	1.89
24	101	199	60	0.00	0.32	0.88	1.35
25	151	199	55	0.00	0.54	1.57	2.43
26	151	199	65	0.00	0.49	1.35	2.11
27	151	199	80	0.00	0.39	1.15	1.79

Notes: (1) The quantity, Z, is the distance from the water injection section to the film removal section.

(2) Tube Diameter, $D=0.497$ in.

(3) Inlet Temperature, $t_1=70^\circ\text{F}$

3LE F.3

MADE FROM THE MOTION PICTURES

	Number of Waves Measured	Frequency F, waves/sec	Average Velocity V _w , ft/sec	Average Disturbance Length L, in.	$\left(\frac{FL}{V_w}\right)$
	58	48.9 ± 6.5	11.9 ± 1.0	0.145 ± .154	0.152 ± .028
	55	36.8 ± 5.6	13.3 ± 1.5	0.142 ± .080	0.102 ± .018
	41	36.9 ± 5.8	13.4 ± 0.9	0.148 ± .086	0.103 ± .018
	97	88.8 ± 8.9	16.8 ± 1.3	0.347 ± .101	0.153 .021
	66	60.4 ± 7.6	19.0 ± 1.0	0.334 ± .064	0.088 .013
	62	55.6 ± 7.1	19.5 ± 1.0	0.340 ± .067	0.081 .012
	94	89.4 ± 9.4	17.2 ± 1.5	0.439 ± .092	0.190 ± .024
	71	59.4 ± 7.3	18.8 ± 1.6	0.498 ± .110	0.131 ± .019
	69	60.9 ± 7.6	19.2 ± 1.5	0.428 ± .100	0.113 ± .017
	133	121.5 ± 10.5	18.5 ± 1.6	0.314 ± .086	0.172 .021
	86	74.4 ± 8.0	19.3 ± 0.9	0.277 ± .049	0.089 .011
	84	74.1 ± 8.2	19.8 ± 0.7	0.294 ± .053	0.092 .012
	135	123.8 ± 10.7	20.1 ± 1.8	0.408 ± .123	0.209 ± .026
	94	83.4 ± 8.6	21.3 ± 1.2	0.370 ± .082	0.120 ± .015
	86	80.9 ± 8.8	22.1 ± 1.2	0.370 ± .085	0.113 ± .015
	263*	124.5 ± 7.7	21.8 ± 1.3	0.506 ± .111	0.242 ± .020
	201*	86.3 ± 6.1	23.0 ± 1.3	0.474 ± .094	0.148 ± .013
	196*	84.6 ± 6.2	23.0 ± 1.3	0.459 ± .089	0.141 ± .013
	154	149.7 ± 12.0	23.1 ± 1.9	0.461 ± .203	0.249 ± .037
	225*	97.9 ± 6.7	23.6 ± 0.9	0.388 ± .054	0.134 ± .010
	214*	95.9 ± 6.2	23.9 ± 0.7	0.308 ± .034	0.103 ± .007

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.2.

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TABLE F.3

RESULTS OF MEASUREMENTS MADE FROM THE MOTION P.

Flow Condition Number	Air Flow Rate W_G , lb _m /hr	Water Flow Rate W_L , lb _m /hr	Inlet Pressure P_1 , psia	Distance From Water Injection Section Z , in.	Number of Waves Measured
5	101	199	90	12.75 71.75 125.25	58 55 41
23	101	199	40	12.75 71.75 125.25	97 66 62
11	151	299	90	12.75 71.75 125.25	94 71 69
15	201	199	90	12.75 71.75 125.25	133 86 84
16	201	299	90	12.75 71.75 125.25	135 94 86
17	201	411	90	12.75 71.75 125.25	263* 201* 196*
21	251	299	90	12.75 71.75 125.25	154 225* 214*

- Notes: (1) The uncertainty limits which are shown in this table are values of the standard deviation calculated as described in Appendix E, Section E.2.
- (2) An asterik next to the number of waves measured indicates that, for that flow condition and distance from the water injection section, data were obtained from more than one roll of film.
- (3) Tube Diameter, $D = 0.497$ in.
- (4) Inlet Temperature, $t_1 = 70^\circ\text{F}$

APPENDIX G

ACCURACY AND REPRODUCIBILITY OF THE EXPERIMENTAL MEASUREMENTS.

G.1 Measurements Which Define a
Particular Flow ConditionG.1.1 Accuracy of Measurements Used to Determine Air Mass Flow Rate

For a particular flow condition, the air mass flow rate was calculated from measurements of the orifice inlet pressure and temperature and pressure drop. This calculation was made using Equation (C-1) in Appendix C. The accuracy of this quantity should therefore depend on the following:

- 1) The accuracy of the measurements of orifice inlet pressure and temperature.
- 2) The accuracy of the measurement of orifice pressure drop.
- 3) The accuracy of the orifice coefficient, K , and compressibility correction, Y .

The scale of the manometer used to measure the pressure drop across the orifice was graduated in inches with 0.1 in. subdivisions. Therefore, the error of observation of this quantity should be less than 0.05 in. As a result, since the orifice pressure drop corresponding to the various air flow rates which were used ranged approximately from 2.3 in. to 55.5 in. of oil, the uncertainty of this measurement probably varied from 0.09 to 2.2 per cent.

The Bourdon gage used to measure the pressure at the orifice inlet was calibrated and found to be accurate to within 0.5 psi. Therefore, since the measured values of this quantity varied approximately from 40 to 95 psia, the accuracy probably ranged from about 0.5 to 1.25 per cent.

The temperature at the orifice inlet was measured by means of a thermocouple installed as described in Appendix C, Section C.10. This thermocouple was calibrated and found to be accurate to within 1°F . Therefore, since the value of the temperature at the orifice inlet ranged from 530°R to 540°R , the accuracy of this measurement was probably 0.2 per cent or less.

Orifice coefficient from A.S.M.E. tables, such as those used to obtain the values given in Figure C.1, are accurate to 0.5 per cent or less providing the orifice is properly located with respect to other flow disturbing elements in the hydraulic system. As pointed out in Appendix C, Section C.4.1, the location of the orifice in the hydraulic system was well within the recommendations given in the Chemical Engineering Handbook (28). Therefore, the value of the orifice coefficient was probably accurate to within 0.5 per cent.

According to Dean (9), values of the compressibility correction, Y , have approximately the same uncertainty as values of K .

Finally, using the methods of calculating the uncertainty of a compound quantity suggested by Topping (32)¹, it is possible to determine the uncertainty of a particular value of the air mass flow rate calculated from Equation (C-1). This uncertainty ranges from 1.4 per cent for the highest air flow rate which was measured to 2.5 per cent for the lowest.

G.1.2 Accuracy of Measurements of Water Flow Rate

The rotameter used to measure the rate of water flow into the

¹These methods are consistently used in this thesis for calculations of this type.

test section was calibrated as described in Appendix C, Section C.4.3. This calibration was repeated three times during the course of the experimental work. In addition, considerable care was taken to prevent fouling of the float or tube. Under these conditions, catalogs published by the manufacturer of this rotameter (The Brooks Rotameter Co.) indicate that the accuracy should be within 1 per cent of the scale reading.

During a particular experimental measurement, it was often necessary to maintain the water flow rate at a particular value for several minutes. As a result, variations from the desired flow rate were caused by a slight drift in the supply pressure of compressed air used to force the water from the supply tank. However, these variations were never allowed to exceed 1 per cent of the measured value. Therefore, the overall uncertainty of a particular value of the water mass flow rate should still be less than 2 per cent.

By conservation of mass, the total water collection rate from the air-water separators should equal the flow rate of water into the test section. However, as a result of the uncertainty associated with each of these quantities, some disagreement would be expected. The uncertainty of the measurement of the flow rate of water entering the test section is 1 to 2 per cent. On the other hand, the uncertainty of the total water collection rate is about 2 per cent (see Section G.2.1 below). Therefore, the uncertainty of the difference could be from 3 to 4 per cent. In order to check this, the per cent difference between each measurement of the total water collection rate and the corresponding water injection flow rate was calculated as described in Appendix E, Section E.1. The results of this check are shown in Figure G.1 as a

FIGURE G.1

HISTOGRAM OF VALUES OF THE PER CENT DIFFERENCE
BETWEEN THE INLET WATER FLOW RATE AND THE
TOTAL COLLECTION RATE

histogram. All except 3 of 979 measurements of total water collection rate were within 3 per cent of the mass flow rate of water entering the test section. However, the distribution is not symmetrical about a value of zero. Instead, the distribution has a most probable value of about -0.5 per cent. In other words, the total water collection rate from the separators was usually slightly less than the flow rate of water entering the test section. The most probable reason for this is that the air-water separators were not 100 per cent efficient. In particular, as pointed out in Appendix C, Section C.8, the manufacturer of these separators only guarantees a 99 per cent efficiency for air flow rates such as those used during the experimental work described in this thesis. Thus, the most probable error indicated in Figure G.1 is within the expected limitations of the air-water separators.

G.1.3 Accuracy of Measurements of Inlet Pressure

The Bourdon gage used to measure the pressure at the inlet to the test section was calibrated with a dead weight gage tester and found to be accurate to within 0.5 psi. Therefore, since the measured values of inlet pressure varied from 40 to 90 psia, the uncertainty of this measurement probably ranges from approximately 0.55 to 1.25 per cent.

G.1.4 Accuracy of Measurements of Temperature

The temperatures of the air and water entering the test section and the temperature of the air leaving the separators located downstream of the test section exit were measured by thermocouples which were installed as described in Appendix C, Section C.10. These thermocouples were calibrated and found to be accurate to within 1°F. Therefore, an individual temperature measurement of 70°F should be accurate to

within approximately 1.4 per cent.

G.1.5 Variation of Tube Diameter

As pointed out in Appendix C, Section C.11, the mean diameter of the vertical tube was 0.497 in. The maximum variation from this value was ± 0.003 in. Therefore the uncertainty of this quantity is approximately 0.6 per cent.

G.1.6 Reproducibility of Particular Values of the Air Mass Flow Rate, Water Mass Flow Rate, Inlet Pressure, and Temperature

During the course of the experimental work, it was necessary to reproduce a given flow condition many times. It was possible to consistently reproduce a particular value of the air mass flow rate to within 1 per cent. Particular values of the water mass flow rate could be reproduced almost exactly. Values of the inlet pressure could be reproduced to within 0.5 psi or approximately 0.5 to 1.25 per cent. However, it was not always possible to maintain the temperatures of the air and water at exactly at 70°F; and, although the average of all temperature measurements for a particular experimental condition was always within 1°F of this value, individual temperature measurements ranged from 67 to 77°F.

G.2 Measurements of Water Collection Rate and Dispersed Water Fraction

G.2.1 Accuracy of Measurements of Water Collection Rate

Measurements of water collection rate from each of the two sets of air-water separators was accomplished by measuring the time required for the water level in the collection tank connected to a given set of separators to increase by a particular amount. For some of the experimental conditions which were studied, the rate of collection was as much as 30 in. per minute. Under these conditions, the finite re-

action time of the observer is a possible source of error. However, it seems reasonable to assume that errors of this type would tend to be the same at each end of the time interval.

The major source of error in the determination of the collection rate from a particular set of separators was probably the conversion of the measured collection rate (in./min) to a mass flow rate (lb_m/hr). This conversion is based on the results of the calibration of the collection tanks given in Appendix C, Section C.9. These results show that the standard deviation of repeated measurements of the conversion factor for a particular tank was approximately 0.7 per cent of the mean value. Therefore, it can be assumed that a value of the water collection rate (lb_m/hr) for a particular set of separators has an uncertainty of approximately 1 per cent. This means that the total water collection rate from both sets of separators would have an uncertainty of as much as 2 per cent.

G.2.2 Accuracy of Values of the Dispersed Water Fraction

For a particular experimental condition, the value of the dispersed water fraction at a particular location downstream of the water injection section was determined from the measurements of the water collection rate as described in Appendix E, Section E.1. This procedure involves the calculation of the ratio of the water collection rate from the set of separators located downstream of the test section to the total water collection rate from both sets of separators. As discussed in Section G.2.1, the uncertainty of the measurements of water collection rate from either set of separators is about 1 per cent. On the other hand, the uncertainty of the total collection rate from both

sets of separators is about 2 per cent. Therefore the resulting uncertainty in the ratio of these two quantities could be as much as 3 per cent.

In addition to the uncertainty resulting from possible inaccuracy of the collection rate measurements, it is also necessary to consider the extent of the uncertainty related to the method of measurement itself. In particular, the question arises as to the effect of removing air through the porous wall along with the water from the film. In order to answer this question, collection rate measurements were made using at least three air bleed rates for each experimental condition. It was found that, for a given condition, the ratio of the water collection rate from the set of separators located downstream of the test section to the total water collection rate was essentially independent of the rate of air removal from the tube, for a sufficiently large value of this parameter. For each of the 237 values of the dispersed water fraction tabulated in Table F.1, it was possible to obtain from 2 to 5 values of the collection rate ratio which were within from 0.001 to 0.005 of the value at the highest air removal rate. Thus, a particular value of the dispersed water fraction could have an uncertainty of as much as 0.005 as a result of the effect of air removal rate.

As result of the uncertainty involved in the measurement of water collection rates and of the uncertainty due to the effect of air removal rate, a dispersed water fraction of 0.05 could have an uncertainty of from 5 to 13 per cent. On the other hand, the uncertainty of a dispersed water fraction of 0.5 should be 4 per cent or less.

G.2.3 Reproducibility of Values of the Dispersed Water Fraction

In order to check the reproducibility of a value of the dispersed water fraction determined for a particular experimental condition, some measurements of this quantity were repeated at the conclusion of the experimental work. It was found that new values of the dispersed water fraction were within 0.001 to .005 of previously determined values for each experimental condition checked.

G.3 Pressure Drop Measurements

The pressure drop between the water injection section and the film removal section was measured with a U tube manometer. The scale of this instrument was graduated in inches with 0.1 in. subdivisions. Therefore, the error of observation involved was probably less than 0.05 in. Hg or 0.025 psi. For the larger pressure drops associated with higher air and water flow rates, this uncertainty increased to approximately 0.1 in. Hg or 0.05 psi as a result of slight fluctuations in the manometer level. Therefore, since the measured values of pressure drop varied from 0.07 to 15.81 psi, the uncertainty ranged from approximately 35 per cent for the lowest value to about 0.3 per cent for the highest value.

With respect to reproducibility, it was found that measurements of pressure drop which were repeated for several experimental conditions were within from 1.5 to 2 per cent of previously measured values.

G.4 Measurements Made from the Motion Pictures

G.4.1 Accuracy of Wave Frequency Measurements

The accuracy of a particular value of wave frequency depends upon the following:

- 1) The accuracy of the measurement of the rotational speed of the timer.
- 2) The accuracy of counting the number of disturbance waves and the corresponding number of timer rotations.

The stroboscope used to measure the rotational speed of the timer had an accuracy of 1 per cent of the dial reading. The only source of error in counting the number of waves would be interpretation. However, since the waves were easily observed, errors of this type were probably not a factor. Similarly, there should be little probability of error in the corresponding number of rotations of the timer. Therefore, the experimental uncertainty of a particular value of wave frequency should not exceed 1 per cent.

G.4.2 Accuracy of Measurements of Wave Disturbance Length

The principal source of error in the measurement of the length of a disturbance wave was interpretation. This resulted from the fact that the limits of a particular wave were not always well defined. The magnitude of the uncertainty involved is difficult to estimate but was probably about 1/16 in. Therefore, since the disturbance length of individual waves varied from 1-1/4 in. to 1/8 in., the corresponding uncertainty probably ranged from approximately 5.5 to 50 per cent. However, for a large number of measurements of this quantity, errors of interpretation should tend to average out. As a result, the corresponding uncertainty of the average value for a particular experimental condition is probably less than the uncertainty of a single measurement.

From Table F.3 of Appendix F, it can be seen that for some flow conditions, the standard deviation of individual values of wave disturbance length about the average value is somewhat greater than

would be expected from random errors of observation alone. Therefore, this quantity is probably statistical to some extent.

G.4.3 Accuracy of Wave Velocity Measurements

The accuracy of a particular measurement of wave velocity depends upon the following:

- 1) The accuracy of the measurement of the rotational speed of the timer.
- 2) The accuracy of the measurements of the distance traveled by the wave and the corresponding number of rotations of the timer.

As discussed in Section G.4.1 above, the uncertainty of a measurement of the rotational speed of the timer was about 1 per cent. The accuracy of the measurement of the distance traveled by the wave would depend on the accuracy of the determination of the wave position at each end of the interval. As in the case of **disturbance** length, this determination probably had an uncertainty of approximately 1/16 in. Therefore, since the distance traveled by a particular wave varied approximately from 1-1/4 in. to 3 in. the uncertainty of this quantity probably ranged from 4 to 10 per cent. The accuracy of measurement of the number of rotations of the timer would depend on the accuracy of the determination of the timer position at each end of the time interval. The timer scale was graduated in intervals of 0.01 revolutions and the accuracy of a particular determination of the timer position was probably no better than this. Therefore, since the number of rotations corresponding to the movement of a particular wave varied from 1 to 2, the uncertainty of this quantity should be 1 per cent or less.

The uncertainty of a particular value of wave velocity resulting from the uncertainties of the measurements used to calculate it could, on the basis of the above estimates, vary from 5 to 11 per cent. However, the principal contribution to this uncertainty is from **observation errors** which, for a large number of measurements should tend to average out. As a result, as in the case of measurements of disturbance length, the experimental uncertainty of the average value of the wave velocity for a particular experimental condition is probably less than the uncertainty of a single measurement.

From Table F.3 of Appendix F, it can be seen that, for some flow conditions, the standard deviation of individual values of wave disturbance length about the average value is somewhat greater than would be expected from errors of observation alone. Therefore, this quantity is probably statistical to some extent.

G.4.4 Reproducibility of Values of Wave Frequency, Average Disturbance Length, and Average Velocity

A check on the reproducibility of values of wave frequency, average disturbance length and average velocity for a particular flow condition gave the following results:

- 1) Measurements of wave frequency made from two different rolls of film for a particular flow condition were consistent to within 1.4 to 7.5 per cent.
- 2) Values of average wave velocity determined from two different rolls of film for a particular flow condition were consistent within 0.5 to 5.4 per cent.
- 3) Values of average disturbance length determined from different rolls of film for a particular flow condition were consistent within 1.3 to 26 per cent.

These results show that reproducibility of the average disturbance length and average velocity is within the uncertainties estimated in Sections G.4.2 and G.4.3. However, this is not true for the wave frequency. This is probably because of the statistical uncertainty of this quantity. In order to show this, values of the statistical standard deviation of a particular value of wave frequency were calculated assuming that the frequency distribution which describes the formation of waves is a Poisson type of distribution. This was done using the computer program described in Appendix E. The results are included in Table F.3 of Appendix F. It was found that calculated values of the standard deviation were from 8 to 16 per cent of the corresponding value of frequency. Thus, it can be concluded that the reproducibility of repeated measurements of wave frequency was within the expected statistical uncertainty.

APPENDIX H

UNCERTAINTIES IN THE ANALYSIS AND CORRELATION
OF THE EXPERIMENTAL RESULTS

The derivation of Equation (5-21) which was used in Chapter V to interpret the experimental results started with the assumption that the rate of entrainment could be expressed as follows:

$$E = B_o \tau_i \Pi D_c (V_c - V_f) N_w \quad (5-6)$$

where B_o is a constant of proportionality, τ_i is the interfacial shear stress (lb_f/ft^2), D_c is the diameter of the core of the tube occupied by the dispersed phase (ft), $(V_c - V_f)$ is the difference between the average velocity of the dispersed phase and the average film velocity (ft/hr) and N_w is the average fraction of the film surface covered by disturbance waves. Then it was assumed that:

- 1) The interfacial shear stress can be related to the total pressure gradient as follows:

$$\tau_i \simeq \frac{1}{B_1} \left| \frac{dP}{dZ} \right| \frac{D_c}{4} \quad (5-9)$$

- 2) The difference between the average velocity of the dispersed phase and the average film velocity can be approximately written:

$$(V_c - V_f) \simeq \frac{1}{B_2} V_G \quad (5-10)$$

- 3) The average fraction of the film surface covered by disturbance waves can be written:

$$N_W \simeq \frac{FL}{V_W} = B_L(Z) W_L^{0.5} \quad (5-17)$$

where $B_L(Z)$ is only a function of distance along the tube.

The approximation expressed by Equation (5-9) assumes that the gravitational and acceleration components of the total pressure gradient are small and that B_1 is therefore a quantity which is slightly greater than unity and approximately constant and independent of flow condition or distance from the water injection section. The use of the approximation expressed by Equation (5-10) assumes similarly that the velocity of the liquid film is small enough so that B_2 is also a quantity which is slightly greater than unity and approximately constant and independent of flow condition or distance from the water injection section. The validity of each of these two assumptions was checked analytically by means of the computer program described in Section E.3 of Appendix E. The results are tabulated in Tables H.1 and H.2.

Calculated values of B_1 are given in Table H.1. From this table, it can be seen that the range of individual values about the average value varies from 9 per cent near the inlet to 3 per cent further downstream of the water injection section.

Calculated values of B_2 are given in Table H.2. From this table it can be shown that the range of individual values of B_2 about the average value at a particular location along the tube varies from 3.9 per cent near the inlet to 2.7 per cent further downstream of the water injection section.

TABLE H.1

VALUES OF THE QUANTITY, B_1

B_1						
23.50 in.	Z=35.25 in.	Z=50.25 in.	Z=71.00 in.	Z=94.75 in.	Z=115.49 in.	Z=127.25 in.
1.023	1.016	1.013	1.013	1.013	1.013	1.013
1.083	1.059	1.050	1.049	1.054	1.059	1.060
1.077	1.025	1.025	1.019	1.019	1.019	1.019
1.078	1.048	1.037	1.030	1.031	1.031	1.031
1.072	1.053	1.039	1.036	1.037	1.040	1.040
1.073	1.049	1.048	1.045	1.050	1.050	1.051
1.102	1.076	1.068	1.064	1.070	1.074	1.077
1.073	1.045	1.040	1.037	1.039	1.041	1.042

TABLE H.1

CALCULATED VALUES OF THE QUANTITIES

Flow Condition Number	Air Flow Rate W_G , lb _m /hr	Water Flow Rate W_L , lb _m /hr	Inlet Pressure P_1 , psia				
				Z=2.87 in.	Z=11.75 in.	Z=23.50 in.	Z=35.25
5	101	199	90	1.043	1.032	1.023	1.01
23	101	199	40	1.105	1.120	1.083	1.05
11	151	299	90	1.119	1.073	1.077	1.02
15	201	199	90	1.094	1.095	1.078	1.04
16	201	299	90	1.162	1.104	1.072	1.05
17	201	411	90	1.239	1.105	1.073	1.04
21	251	299	90	1.201	1.143	1.102	1.07
Average Values of B_1				1.138	1.096	1.073	1.04

Notes: (1) B_1 is defined by Equation (5-9).

(2) Z is the distance from the water injection section.

(3) Tube Diameter, D = 0.497 in.

(4) Inlet Temperature, $t_1 = 70^\circ\text{F}$.

TABLE H.2

VALUES OF THE QUANTITY, B_2

B_2						
Z=23.50 in.	Z=35.25 in.	Z=50.25 in.	Z=71.00 in.	Z=94.75 in.	Z=115.49 in.	Z=127.25 in.
1.136	1.135	1.134	1.135	1.133	1.130	1.130
1.077	1.075	1.074	1.070	1.067	1.063	1.062
1.142	1.143	1.141	1.140	1.137	1.134	1.132
1.103	1.099	1.098	1.095	1.093	1.090	1.089
1.126	1.122	1.121	1.117	1.113	1.109	1.107
1.147	1.145	1.141	1.135	1.130	1.126	1.122
1.112	1.107	1.105	1.100	1.094	1.090	1.086
1.120	1.118	1.116	1.113	1.110	1.106	1.103

TABLE H.2

CALCULATED VALUES OF THE QUANTITIES

Flow Condition Number	Air Flow Rate W_G , lb/hr m	Water Flow Rate W_L , lb/hr m	Inlet Pressure P_1 , psia				
				Z=2.87 in.	Z=11.75 in.	Z=23.50 in.	Z=35.00 in.
5	101	199	90	1.154	1.147	1.136	1.125
23	101	199	40	1.091	1.083	1.077	1.070
11	151	299	90	1.163	1.156	1.142	1.129
15	201	199	90	1.120	1.113	1.103	1.093
16	201	299	90	1.141	1.136	1.126	1.115
17	201	411	90	1.158	1.156	1.147	1.135
21	251	299	90	1.131	1.120	1.112	1.102
Average Values of B_2				1.137	1.130	1.120	1.110

Notes: (1) B_2 is defined by Equation (5-10).

(2) Z is the distance from the water injection section.

(3) Tube Diameter, $D = 0.497$ in.

(4) Inlet Temperature, $t_1 = 70^\circ\text{F}$.

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The use of the approximation expressed by Equation (5-17) assumes that $B_4(Z)$ is a quantity which is only a function of distance from the water injection section. From Figure 5.6 it can be seen that the range of individual values of $B_4(Z)$ about the average value at a particular location along the tube is approximately 12.5 per cent. However, from Table F.3, it can be shown that the standard deviation of calculated values of $\left(\frac{FL}{V_W}\right)$ varies from 7.1 to 18.6 per cent of a particular value of this quantity. Thus, assuming that the uncertainty of a particular value of the water flow rate is approximately 2 per cent, the uncertainty of a particular value of $B_4(Z)$ calculated from Equation (5-17) could range from 9.1 to 20.6 per cent. Thus the range of values of $B_4(Z)$ shown in Figure 5.6 is probably within the experimental uncertainty. However, to some extent this range could also be a result of the fact that $B_4(Z)$ is not entirely independent of variables such as W_G and P_L or that the exponent of W_L in Equation (5-17) is not exactly 0.5.

By combining the uncertainties involved in the assumptions that values of B_1 , B_2 , and $B_4(Z)$ are constant at a particular position along the tube, it can be shown that the range of values of the left side of Equation (5-21) could vary from 25.4 per cent near the inlet to 18.2 per cent further downstream of the water injection section.

From Figure 5.7, it can be observed that the range of individual values of the left side of Equation (5-21) varies from 25 per cent at a short distance from the water injection section to approximately 35 per cent further downstream. Thus, at a large distance from the water injection section, the range is about 17 per cent

greater than would be expected from the preceding discussion. This is probably because of the experimental uncertainty of the values of W_d , P , W_G , and W_L used to calculate a particular value of this quantity. As an example of this uncertainty, consider the data points in Figure 5.7 which correspond to the following flow condition:

$$W_G = 101 \text{ lb/hr}$$

$$W_L = 199 \text{ lb/hr}$$

$$P_1 = 90 \text{ psia}$$

For this condition, the change in the dispersed water fraction from $Z = 59.25$ in. to $Z = 130.25$ in. is approximately .008. Assuming that the absolute uncertainty of a particular value of the dispersed water fraction is at least .001, the absolute uncertainty of the difference between the values at $Z = 59.25$ in. and $Z = 130.25$ in. could be as much as .002. Thus the experimental uncertainty of dW_d/dZ in the expression on the left side of Equation (5-21) could be as much as 25 per cent. The experimental uncertainties of $\frac{dP}{dZ}$, W_G , $W_L^{0.5}$ would be in addition to this. Thus, it can be concluded that the fact that the range of individual values of the left side of Equation (5-21) about the average value at a particular location along the tube is probably within the uncertainty due to: (1) assumptions made in the derivation of this equation and (2) the uncertainties of the experimental results used to calculate a particular value of this quantity.

APPENDIX I

LIST OF NOMENCLATURE

A	Total cross sectional flow area, ft^2 .
A_c	Cross sectional area of the core or dispersed phase, ft^2 .
B_0	Constant in Equation (5-6), $\text{lb}_m/\text{ft lb}_f$.
B_1	Constant defined by Equation (5-9), dimensionless.
B_2	Constant defined by Equation (5-10), dimensionless.
B_3	Constant defined by Equation (5-16), dimensionless.
$B_4(Z)$	Quantity defined by Equation (5-17), $(\text{lb}_m/\text{hr})^{-0.5}$
$B_5(Z)$	Quantity defined by Equation (5-22), $(\text{lb}_m/\text{hr})^{-0.5}$
C	Average concentration of water in the dispersed phase, lb_m/ft^3 .
D	Tube or pipe inside diameter, ft.
D_c	Diameter of the core or dispersed phase, ft.
D_o	Orifice diameter, ft.
E	Rate of entrainment, $\text{lb}_m/\text{hr ft}$.
F	Frequency of disturbance waves, waves/sec.
g	Gravitational acceleration, $4.17 \times 10^8 \text{ ft/hr}^2$.
g_c	Dimensional constant, $4.17 \times 10^8 \text{ lb}_m\text{ft}/\text{lb}_f\text{hr}^2$.
h	Local heat transfer coefficient, $\text{BTU/hr ft}^2 \text{ } ^\circ\text{F}$.
h_{fg}	Enthalpy of vaporization, BTU/lb_m .
H	Length of the heated section of a tube, ft.
k	Ratio of the specific heat of air at constant pressure to the specific heat of air at constant volume, dimensionless.
K	Orifice coefficient given by Figure C.1, dimensionless.
ℓ	Distance from the inlet of the heated section of a tube, ft.

L	Wave disturbance length, ft.
N_G	Dimensionless quantity defined by Equation (6-1)
$(N_R)_f$	Reynolds number of the water film defined by Equation (6-7), dimensionless.
$(N_R)_p$	Reynolds number based on pipe inside diameter as defined by Equation (C-2), dimensionless.
N_{ST}	Dimensionless quantity defined by Equation (6-4).
N_W	Average fraction of the surface of the water film covered by disturbance waves, dimensionless.
P	Static pressure, psia.
P_1	Pressure immediately downstream of the porous bronze cylinder of the water injection section, psia.
P_3	Pressure immediately upstream of the rotameter used to measure bleed rate from air-water separation and water collection system.
P_o	Pressure immediately upstream of orifice, psia.
ΔP	Total pressure drop between location of water injection section and location of film removal section, psi.
ΔP_b	Pressure drop across wall of porous bronze cylinder in water injection section, lb_f/ft^2 .
ΔP_o	Pressure drop across orifice, in. oil or in. water.
Q	Power, BTU/hr.
Q_c	Critical power, BTU/hr.
Q_G	Volumetric flow rate of air, scfm or cfm.
Q_{G3}	Air bleed flow rate, scfm or cfm.
Q_L	Volumetric flow rate of water, cfm.
Δr	Wall thickness of porous bronze cylinder in water injection section, ft.
R	Gas constant in Equation (5-12), $\text{ft lb}_f/\text{lb}_m^\circ\text{R}$.
S	Force per unit area due to surface tension, lb_f/ft^2 .
t_1	Average temperature of air and water entering the test section, $^\circ\text{F}$.
t_c	Average temperature of the dispersed phase, $^\circ\text{F}$.

t_s	Saturation temperature, °F.
t_w	Temperature of inside surface of the tube wall, °F.
T_o	Absolute temperature immediately upstream of orifice, °R.
T_3	Absolute temperature immediately upstream of the rotameter used to measure bleed rate from air-water separation and water collection system, °R.
V_c	Average velocity of the dispersed phase, ft/hr.
V_d	Average velocity of the dispersed water droplets, ft/hr.
V_f	Average velocity of water film, ft/hr.
V_G	Average air velocity, ft/hr.
V_G^*	Dimensionless quantity defined by Equation (B-1).
V_{GS}	Superficial air velocity calculated by neglecting the presence of water in the tube, ft/sec.
V_L^*	Dimensionless quantity defined by Equation (B-2).
V_{LS}	Superficial water velocity calculated by neglecting the presence of air in the tube, ft/sec.
$(V_{LS})_b$	Superficial water velocity based on total flow area provided by bronze cylinder in water injection section, ft/sec.
V_W	Average velocity of disturbance waves, ft/sec.
W	Total mass flow rate of steam and water, lb/hr.
W_d	Mass flow rate of dispersed water, lb/hr.
W_{d1}	Mass flow rate of dispersed water at $l = 0$, lb/hr.
W_{d2}	Mass flow rate of dispersed water at $l = H$, lb/hr.
W_f	Mass flow rate of the water film, lb/hr.
W_{f1}	Mass flow rate of the water film at $l = 0$, lb/hr.
W_{f2}	Mass flow rate of the water film at $l = H$, lb/hr.
W_G	Mass flow rate of air or steam, lb/hr.
W_L	Mass flow rate of water, lb/hr.
W_{L1}	Mass flow rate of water at $l = 0$, lb/hr.

X	Quality, W_G/W , dimensionless.
X_1	Quality at $l = 0$, dimensionless.
Y	Compressibility correction factor in Equation (C-1), dimensionless.
Z	Distance downstream of the water injection section, ft. (In the case of measurements of dispersed water fraction, this distance is measured from the center of the bronze insert in the water injection section to the center of the bronze insert in the film removal section. In the case of the motion pictures, this distance is measured to the center of the Plexiglas viewing section.)

Greek Letters

α	Permeability coefficient for flow through porous media as defined by Equation (C-10), ft^2 .
β	Ratio of orifice diameter to pipe inside diameter, dimensionless.
γ	Ratio of the average air velocity to the average velocity of dispersed water droplets, dimensionless.
δ	Thickness of the water film, ft.
Δ	Rate of deposition on the film surface of water droplets from the dispersed phase, $\text{lb}_m/\text{hr ft}$.
K	Mass transport coefficient defined by Equation (5-2), ft^2/hr .
μ_G	Air viscosity, $\text{lb}_m/\text{ft hr}$.
μ_L	Water viscosity, $\text{lb}_m/\text{ft hr}$.
π	Constant, 3.14.
ρ_c	Average density of the dispersed phase, lb_m/ft^3 .
ρ_G	Air density, lb_m/ft^3 .
ρ_L	Water density, lb_m/ft^3 .
σ	Surface tension, lb_f/ft .
τ_i	Shear stress at the surface of the water film, lb_f/ft^2 .

ϕ Heat flux, BTU/hr ft².

ϕ_c Critical heat flux, BTU/hr ft².

APPENDIX J

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APPENDIX K

LOCATION OF ORIGINAL DATA, COMPUTER PROGRAM LISTINGS, IBM
CARDS, AND MOTION PICTURE FILMS

Copies of the original data, IBM cards containing the original data, listings and IBM cards for the computer programs, and most of the motion picture films are in the possession of Professor Henri Fenech at M.I.T.

The original data and some of the motion picture films are in the possession of the author.

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APPENDIX L

BIOGRAPHICAL NOTE

The author was born in Springfield, Ohio, on March 30, 1936; but his family moved to Columbus, Ohio, in 1941. In Columbus, he attended the local public schools until graduating from North High School in June, 1953.

The author entered Ohio University in September, 1953 with the help of a scholarship from the Denison Engineering Co. During the summers of 1954, 1956, 1957 and 1958, he held positions with the Denison Engineering Co., the Denison Research Foundation and North American Aviation. In addition, he served as a laboratory assistant and part-time instructor in mechanical engineering at Ohio University during the school years, 1956-57 and 1957-58.

In September, 1957, the author married Alice McBride of Dayton, Ohio.

In June, 1958, the author received a Bachelor of Science degree in Mechanical Engineering. In September of the same year, he entered the Massachusetts Institute of Technology. During the next two years, he held a first year AEC Fellowship and served as a graduate research assistant. In June, 1960, he received Master of Science degrees in Nuclear and Mechanical Engineering. At this time he accepted employment as a reactor supervisor at the MIT Nuclear Reactor Facility.

In September, 1963, the author returned to full time graduate study. During the next three years, he was the recipient of second and third year AEC fellowships and a NASA Traineeship while

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completing requirements for the Doctor of Science degree in Nuclear Engineering.

The author is an associate member of the American Nuclear Society and the American Society of Mechanical Engineers. He is also a member of Sigma Xi, Phi Kappa Phi, Omicron Delta Kappa, Tau Beta Pi and Phi Eta Sigma.

The author is presently employed by the Yankee Atomic Electric Company in Boston, Massachusetts.