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A METHOD OF CORRELATING HEAT TRANSFER DATA FOR SURFACE BOILING OF LIQUIDS

BY

WARREN M. ROHSENOW

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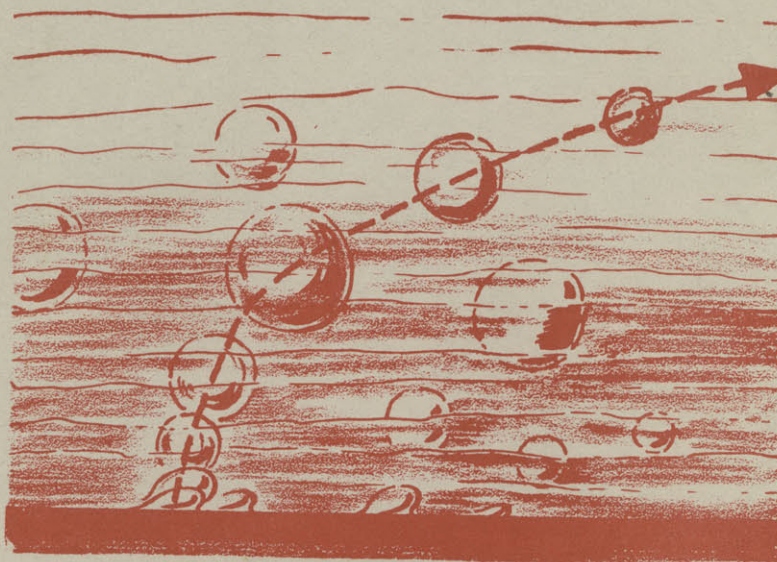
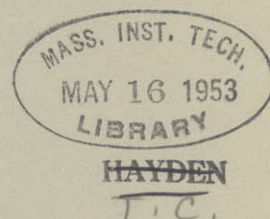
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A METHOD OF CORRELATING HEAT TRANSFER DATA
FOR SURFACE BOILING OF LIQUIDS

by

Warren M. Rohsenow*

SUMMARY

A method based on a logical explanation of the mechanism of heat transfer associated with the boiling process is presented for correlating heat transfer data for nucleate boiling of liquids for the case of pool boiling. The suggested relation is

$$\frac{C_s T_x}{h_{fg}} = C_{sf} \left(\frac{g/A}{\mu_l h_{fg}} \sqrt{\frac{g_0 \sigma}{g(\rho_l - \rho_v)}} \right)^{0.33} \left(\frac{C_p \mu_l}{k_l} \right)^{1.7}$$

where the various fluid properties are evaluated at the saturation temperature corresponding to the local pressure and C_{sf} is a function of the particular heating surface-fluid combination.

Heat transfer data for forced convection flow without boiling is correlated by the normal Nusselt number, Reynolds number based on pipe diameter and Prandtl number. For pool boiling with essentially saturated liquids, Jakob (1) shows that the heat transfer from the surface is for the most part transferred directly to the liquid, the increased heat transfer rate associated with boiling being accounted for by the resulting agitation of the fluid by motion of the liquid flowing behind the wake of the bubble departing from the surface. Rohsenow and Clark (2) showed a similar result in studying motion pictures of McAdams (3) for subcooled liquids flowing in forced convection with surface boiling but no net generation of vapor. Gunther and Kreith (4) and Gunther (5)

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presented photographic evidence that in highly subcooled liquids in pool boiling and in forced convection with surface boiling, the bubbles could form at the surface, grow, and then collapse while remaining attached to the surface. Nevertheless the increased heat transfer in boiling was attributed to the agitation of the liquid by the bubble motion.

As the rate of heat transfer is increased and bubble agitation becomes more vigorous the effect of forced convection fluid velocity and hence Reynolds number based on pipe diameter becomes less and less. This effect is shown by the data of Rohsenow and Clark (6) reproduced here in figures 1 and 2. This data is representative of data of others for surface boiling with forced convection. In these figures the curves for various fluid velocities are seen to merge into one curve, showing that as the boiling becomes more vigorous, the effect of fluid velocity disappears. It seems reasonable then to seek a correlation of the heat transfer data by means of a bubble Reynolds number based on bubble diameter and velocity.

For purposes of analysis one can visualize a number of streams of bubble receding from the heating surface and a bubble Reynolds number defined by

$$N_{Re,b} \equiv \frac{G_b D_b}{\mu_l} \quad \text{--- (1)}$$

based on the mass velocity of the bubbles and their diameter as they leave the surface. This quantity is a measure of the local agitation of the fluid at the heating surface and hence is analogous to the ordinary pipe Reynolds number which is a measure of the turbulence in the stream.

To evaluate the bubble Reynolds number, characteristics of bubbles in pool boiling will be employed since there is more detailed visual evidence available for this case than there is for forced convection surface boiling.

Results of these bubble characteristics are compiled by Jakob (1). The heat transfer to the bubbles while attached to the surface can be written with good approximation (2) as

$$\left(\frac{q}{A}\right)_b = h_{fg} \rho_v n \frac{\pi}{6} D_b^3 f \quad \text{----- (2)}$$

Fritz (8) presents a relation for the diameter of the bubble as it leaves the surface, which may be written in the form

$$D_b = C_d \beta \sqrt{\frac{2g\sigma}{g(\rho_l - \rho_v)}} \quad \text{----- (3)}$$

where β is the angle of contact of the bubble as shown in figure 3. Jakob (9) has shown for vapor bubbles of water and of carbon tetrachloride a relation exists between the frequency of bubble formation at a favored point on the surface and the diameter of the bubble when it leaves the surface. This relation can be approximated by the equation

$$f \cdot D_b = C_{fd}, \text{ constant} \quad \text{----- (4)}$$

without serious error.

Inspecting the terms of equation (2) in the light of equations (3) and (4) shows that $(q/A)_b$ is proportional to n for a given operating pressure, ~~β does not change with pressure~~, since all other quantities are functions of saturation pressure alone or are constant. Experiments have shown that bubbles form at selective points on surface forming swaying columns of bubbles. Jakob (7) found that the number of columns or points of origin of bubbles was very nearly directly proportional to the rate of heat transfer from the heating surface for a given operating pressure. Therefore $q/A \approx (q/A)_b$ and can be

written as

$$\frac{g}{A} = C_g h_{fg} \rho_v n \frac{\pi}{6} D_b^3 f \quad \text{----- (5)}$$

where C_g may be a function of pressure.

The mass velocity of the vapor bubbles leaving the surface may be written as

$$G_b = \frac{\pi}{6} D_b^3 f \rho_v n \quad \text{----- (6)}$$

Equations (3), (5) and (6) may be substituted into equation (1) to obtain an expression for the bubble Reynolds number as

$$N_{Re,b} = C_R \beta \frac{g/A}{h_{fg} \rho_v} \sqrt{\frac{g \sigma}{g(\rho_l - \rho_v)}} \quad \text{----- (7)}$$

where D_b , G_b and n have been eliminated, and $C_R = \sqrt{2} C_d / C_g$. The term $[(g/A) / (h_{fg} \rho_v)] [g \sigma / g(\rho_l - \rho_v)]^{1/2}$ is dimensionless and β has the dimensions radians of angle.

In applying this reasoning to attempt to correlate heat transfer data in the boiling regime it would seem that a bubble Nusselt number would be useful, defined as

$$N_{Nu,b} = \frac{h D_b}{k_l} \quad \text{----- (8)}$$

This quantity has been defined and utilized by Jakob (1)(16). Substituting equation (3) into equation (8) results in

$$N_{Nu,b} = C_N \beta \frac{1}{k_l} \sqrt{\frac{g \sigma}{g(\rho_l - \rho_v)}} \quad \text{----- (9)}$$

where $C_N = \sqrt{2} C_d$. Here, too, the term $(1/k_l) [g \sigma / g(\rho_l - \rho_v)]^{1/2}$ is dimensionless.

Since the postulated mechanism of heat transfer indicates that most of

the heat transfer goes directly from the wall to the liquid, and since the Prandtl number is significant in relations for heat transfer to a non-boiling fluid, it should probably be included in the correlation for heat transfer to a boiling fluid. Then the correlation suggested is

$$N_{Nu,b} = \phi_1 (N_{Re,b}, N_{Pr}) \quad \text{----- (10)}$$

where $c_p, \mu, k, \sigma, \beta, \rho$ are all evaluated at the saturation temperature corresponding to the local pressure. The above relation applies to the region of vigorous boiling where the fluid velocity or pipe Reynolds number does not influence the heat transfer rate. It would also apply to the case of pool boiling. In the case of surface boiling with forced convection and not very vigorous boiling where the fluid velocity does influence the heat transfer rate, some form of a pipe Reynolds number might be added to the right side of equation (10). There is some doubt that the ordinary pipe Reynolds number would be significant because the motion of the bubbles might tend to destroy the normal relationship between viscous and inertia forces.

Contact Angle, β

The bubble contact angle, β , shown in figure 3, is determined by the values of σ_{sl}, σ_{lv} and σ_{vs} ; hence it is determined both by the kind of fluid and the kind of heating surface. All of the other properties in the expressions for bubble Reynolds number and bubble Nusselt numbers are functions of the fluid alone. The angle β from figure 3 is seen to be related to the various surface tensions by the relation

$$\cos \beta = \frac{\sigma_{sl} - \sigma_{vs}}{\sigma_{lv}} \quad \text{----- (11)}$$

For lack of available information the effect of pressure on β was

disregarded in applying equation (10) to existing data. This assumption is equivalent to assuming that the effect of pressure on the values of ρ, σ and σ_{vs} of figure 3 is such that the angle β remains independent of pressure. In applying equation (10) to the correlation of experimental data the terms C_R, C_n and β will be omitted.

Effect of Liquid Subcooling

In pool boiling the primary region of interest is the case in which the liquid temperature is essentially at the saturation temperature. However, in forced convection with surface boiling the liquid temperature may be greatly subcooled. It has been shown by many experimenters that the effect of subcooling of the liquid may be eliminated if the data is plotted as q/A vs T_x as shown in figures 1 and 2. Hence defining the film coefficient in the bubble Nusselt number as $h_x = (q/A) \div T_x$ eliminates the necessity of including liquid subcooling as a variable in a correlation.

OTHER FORMS OF THE PROPOSED CORRELATION EQUATION

Since both the bubble Reynolds number and the bubble Nusselt number embody a (q/A) term, it will be desirable to employ the term

$$\frac{N_{Re,b} N_{Pr}}{N_{Nu,b}} = \frac{C_p T_b}{h_{fg}} \quad \text{----- (12)}$$

This dimensionless group is the ratio of liquid superheat enthalpy at the surface temperature to the latent enthalpy of evaporation.

The equation (10) may be replaced by

$$N_{Re,b} = \phi_2 \left(\frac{C_p T_b}{h_{fg}}, N_{Pr} \right) \quad \text{----- (13)}$$

CORRELATION OF EXPERIMENTAL DATA

Pool Boiling:

The proposed correlation equation (13) has been applied to the data of various experimenters. It will be of interest to observe in some detail its

application to the data of Addoms (10) for pool boiling of water because of the wide range of pressures covered -- 14.7 psia to 2465 psia. In these experiments degassed, distilled water was boiled by an electrically heated horizontal platinum wire. Data for a wire diameter of 0.024 inches is shown in figure 4a. A plot of $[(q/A)/\mu_x h_{fg}][g_0\sigma/g(p_2-p_v)]^{1/2}$ vs $C_2 T_x/h_{fg}$ is shown in figure 4b. On this plot the position of the lines rises to a maximum with pressure and then falls again. At the pressure corresponding to the highest line on this plot, the Prandtl number is very nearly at its minimum value according to the data tabulated by Wellman (11). Hence this effect appears to be a Prandtl number effect, which was anticipated in the analysis. A cross-plot of $C_2 T_x/h_{fg}$ vs N_{Pr} for constant values of bubble Reynolds number shows the slope of the line on a log-log plot to be approximately 1.7; hence the final correlation as shown in figure 4c results in an equation of the form

$$\frac{C_2 T_x}{h_{fg}} = C_{sf} \left(\frac{q/A}{\mu_x h_{fg}} \frac{g_0\sigma}{g(p_2-p_v)} \right)^{0.33} \left(\frac{C_2 \mu_f}{k_x} \right)^{1.7} \quad \text{--- (14)}$$

where the value of C_{sf} is 0.013 with a spread of data of approximately $\pm 20\%$.

This process was repeated for some of the data of Cichelli and Bonilla (12) who boiled various fluids on a polished chromium-plated, horizontal plate which was electrically heated. The results of the proposed correlation are shown in figures 5 through 7. In each case the resulting equations are of the form of equation (14). Only the data for single component fluids on clean surfaces were correlated.

The data of Cryder and Finalborgo (15) is shown correlated in figure 8. In every case the correlation equation (14) was applied and the resulting values of C_{sf} are listed in Table I.

Table I

<u>Reference</u>	<u>Fluid-Heating Surface</u>	<u>C_{sf}</u>
Addoms(10)	Water - Platinum	0.013
Cichelli-Bonilla(12)	Benzene - Chromium	0.010
Cichelli-Bonilla(12)	Ethyl Alcohol - Chromium	0.0027
Cichelli-Bonilla(12)	n-Pentane-Chromium	0.015
Cryder-Finalborgo(15)	water - Brass	0.0060

Forced Convection with Surface Boiling:

In order to show the effect of forced convection flow on the boiling process plots of $N_{Re,b}$ vs $(C_x T_x / h_{fg}) N_{Pr}^{1.7}$ were made for the surface boiling data of Rohsenow and Clark (6)(13) for degassed distilled water flowing in a vertical nickel tube 0.180" diameter 9.4" long and for the data of Kreith and Summerfield (14) for degassed distilled water flowing in a stainless steel tube 0.587" diameter 17.5" long. Superimposed on these plots, figures 9 and 10, is the correlation line for the pooling boiling data for water from figure 4c.

Lines of constant forced convection velocity and pressure are seen to merge toward a single line which would probably be parallel to this line for pool boiling from figure 4c. When the boiling becomes more vigorous at the higher values of T_x , the effect of forced convection fluid velocity apparently disappears. In this region the motion of the bubbles seems to control the mechanism of heat transfer due to fluid agitation.

EVALUATION OF FLUID PROPERTIES

In these correlations the fluid properties have been evaluated as properties of liquid at the saturation temperature. This was done both for the case of pool boiling with saturated liquid and for the case of surface boiling in forced convection of a subcooled liquid. In each case the liquid near the

heating surface is very nearly at saturation temperature or possibly even at a metastable superheated temperature. Properties of the liquid were used for the C , μ , and k values in the bubble Nusselt number, the Prandtl number, and the new term $C_p T_x / h_{fg}$ because the heat transfer was found to occur primarily by transfer of heat directly from the heating surface to the liquid. The value of μ of the bubble Reynolds number was evaluated as a property of liquid because viscous forces acting to retard the motion of the bubble are those of the liquid.

DISCUSSION OF RESULTS

The results shown in figures 4 through 10 are essentially plots of q/A vs T_x each multiplied by a judicious combination of fluid properties thus effecting the correlation. It is readily observed that q/A rises rapidly with small changes in T_x . Further, the magnitude of T_x is rather small, being of the order of 50 F for water at atmospheric pressure and of the order of 5 or 10 F for water at 2000 psia. In all of the data correlated here the energy was supplied by electricity; hence T_x became the dependent variable in each case. It is difficult to measure the heating surface temperature directly when electric heating is employed. It must be calculated from other measured values such as outer tube surface temperature or resistance of the heating wire. The value of T_x is obtained by subtracting the saturation temperature from this determined heating surface temperature. Since the magnitude of T_x is small, any errors in the determined value of heating surface temperature will be greatly magnified in the resulting value of T_x . This can possibly account for some of the difference in the value of C of equation (14) as obtained by various experimenters.

It is, of course, essential in obtaining a correlation of data that the properties of the fluid employed be correct. Any error in the values for these

properties is directly reflected in the data correlation.

Probably the most significant cause of the difference in the values of C is the result of omitting, for lack of currently available information, the term β from the bubble Reynolds number and the bubble Nusselt number in arriving at the correlation as applied. The effect of this is to cause C to be a function of β which is determined by the character of and the kind of heating surface and by the properties of the fluid as shown by equation (11). There is then good reason to expect a different value of C to result for every combination of kind of surface and kind of fluid. Additional information regarding the values of β for various combinations of surfaces and fluids should clarify this matter and produce a valid correlation for all such combinations.

In arriving at equation (5) and hence equations (7) and (9), the expressions for bubble Reynolds number and bubble Nusselt number, it was assumed that β did not vary with pressure for a particular combination of fluid and heating surface. This assumption may account for some of the small spread of the final correlation for each surface-fluid combination. The assumption appears to be fairly good, nevertheless, since the data for a particular fluid-heating surface combination is correlated within about $\pm 20\%$ by equation (14).

It is not suggested that the exponents 0.33 and 1.7 of equation (14) are the true values nor that the form of equation (14) is the best one. Rather it is suggested that the dimensionless groups of equation (14) are significant in correlation boiling heat transfer data. Much more data was correlated than is presented here. Only the data for single component fluids on clean surfaces are presented here. They seemed to be correlated quite adequately by equation (14) with the exponents of 0.33 and 1.7. The 0.33 exponent of the bubble Reynolds number appeared to be adequate for most of the data whether the heating surface was clean or not, but the 1.7 exponent appeared to be valid only for clean surfaces. With dirty surfaces the value of this exponent was quite

erratic, varying between 0.8 and 2.0.

For purposes of comparison the correlation equation (14) may be re-written in the form

$$\frac{q/A}{T_x k_l} \sqrt{\frac{g_0 \sigma}{g(\rho_l - \rho_v)}} = \frac{1}{C_{sf}} \left(\frac{q/A}{\mu_l h_{fg}} \sqrt{\frac{g_0 \sigma}{g(\rho_l - \rho_v)}} \right)^{0.667} \left(\frac{C_l \mu_l}{k_l} \right)^{-0.7} \quad (15)$$

or

$$N_{Nu,b} = \frac{1}{C_{sf}} N_{Re,b}^{0.667} N_{Pr}^{-0.7}$$

which may be compared with the non-boiling forced convection expression

$$N_{Nu} = C_2 N_{Re}^m N_{Pr}^{1/3} \quad (16)$$

where m is in the range of 0.5 to 0.7 when the flow area varies along the direction of flow, e.g., for flow across tubes, around spheres or cylinders, or across interrupted fins.

CONCLUSIONS

Data for pool boiling of a liquid on a clean surface can be correlated by an equation of the form:

$$\frac{C_l T_x}{h_{fg}} = C_{sf} \left(\frac{q/A}{\mu_l h_{fg}} \sqrt{\frac{g_0 \sigma}{g(\rho_l - \rho_v)}} \right)^{0.33} \left(\frac{C_l \mu_l}{k_l} \right)^{1.7}$$

Further experimental work is needed to study the variation of bubble contact angle β and coefficient C_{sf} with pressure and with type of heating surface fluid combination.

Further experimental work is needed to study the validity of equations (3), (4) and (5) which were used in obtaining the terms $(C_l T_x / h_{fg})$, bubble Reynolds number and bubble Nusselt number.

ACKNOWLEDGEMENT

Thanks are due to Dr. J. N. Adams for permission to use his data shown in figure 4 and to Mr. Fakhri Rahmatallah for performing most of the calculations required in preparing this report.

NOMENCLATURE

$C_d, C_{fd}, C_q,$	Coefficients in equations (3), (4), (5), (9), (7), respectively.
C_n, C_R	
C_{sf}	Coefficient of equation (14), which depends upon the nature of the heating surface-fluid combination.
D_b	Diameter of the bubble as it leaves the heating surface, ft.
G_b	Mass velocity of bubbles at their departure from the heating surface, $lb_m/hr ft^2$.
$N_{Nu,b}$	Bubble Nusselt number, defined by equations (8) and (9).
N_{PR}	Prandtl number = $C_p \mu / k_l$
$N_{Re,b}$	Bubble Reynolds number, defined by equations (1) and (7).
T_x	Heating surface temperature minus saturation temperature, F.
C_l	Specific heat of saturated liquid, $Btu/lb_m F$.
f	Frequency of bubble formation, 1/hr.
g	Acceleration of gravity.
g_c	Conversion factor, $4.17 \times 10^8 (lb\ mass)(ft)/(hr^2)(pounds\ force.)$
h_{fg}	Latent heat of evaporation, Btu/lb_m
h_x	$q/A \div T_x$, film coefficient of heat transfer, $Btu/hr ft^2 F$.
k_l	Thermal conductivity of saturated liquid, $Btu/hr ft F$.
m	Number of points of origin of bubble columns per ft^2 of heating surface.
$(q/A)_b$	Heat transfer rate to bubble per unit heating surface area while bubble remains attached to the surface, $Btu/hr ft^2$.
q/A	Heat transfer rate per unit heating surface area, $Btu/hr ft^2$.
β	Bubble contact angle, defined in figure 3.
σ, σ_{lv}	Surface tension of liquid-vapor interface, lb_f/ft
σ_{vs}	Surface tension of vapor-solid interface, lb_f/ft
σ_{sl}	Surface tension of solid-liquid interface, lb_f/ft
ρ_l	Density of saturated liquid lb_m/ft^3

ρ_v Density of saturated vapor lb_m/ft^3

μ_l Viscosity of saturated liquid, $\text{lb}_m/\text{ft hr.}$

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LIST OF ILLUSTRATIONS

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5	Correlation of Data of Cichelli-Bonilla (12) for Chromium-Benzene Interface for Pool Boiling.
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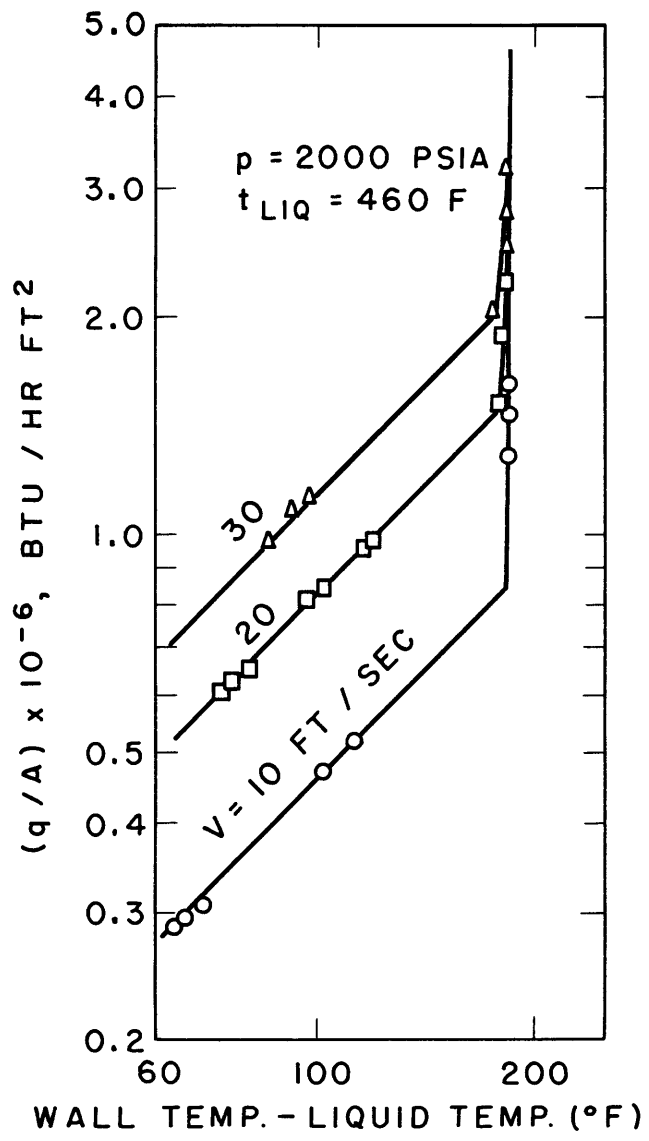


FIGURE 1

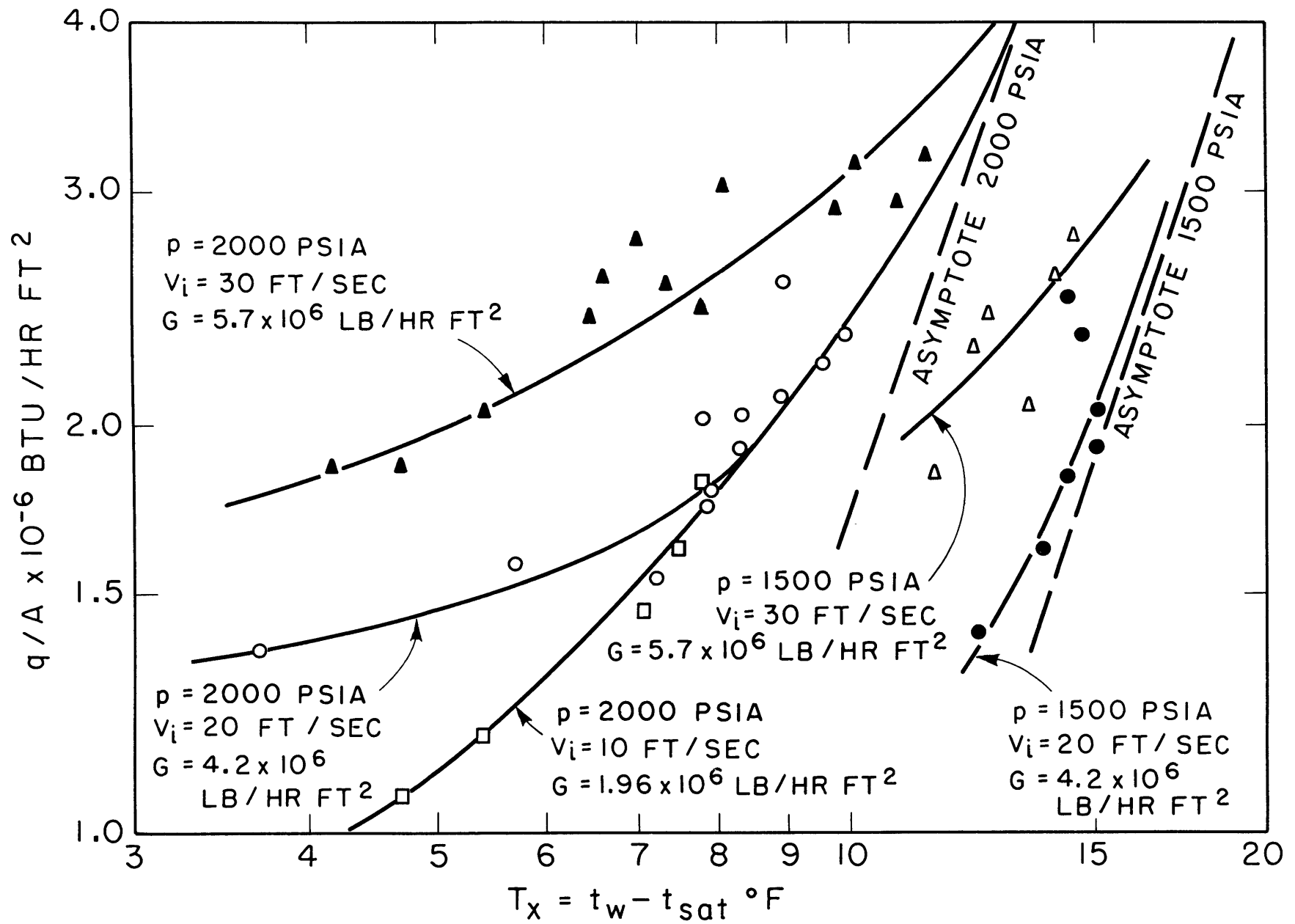


FIGURE 2

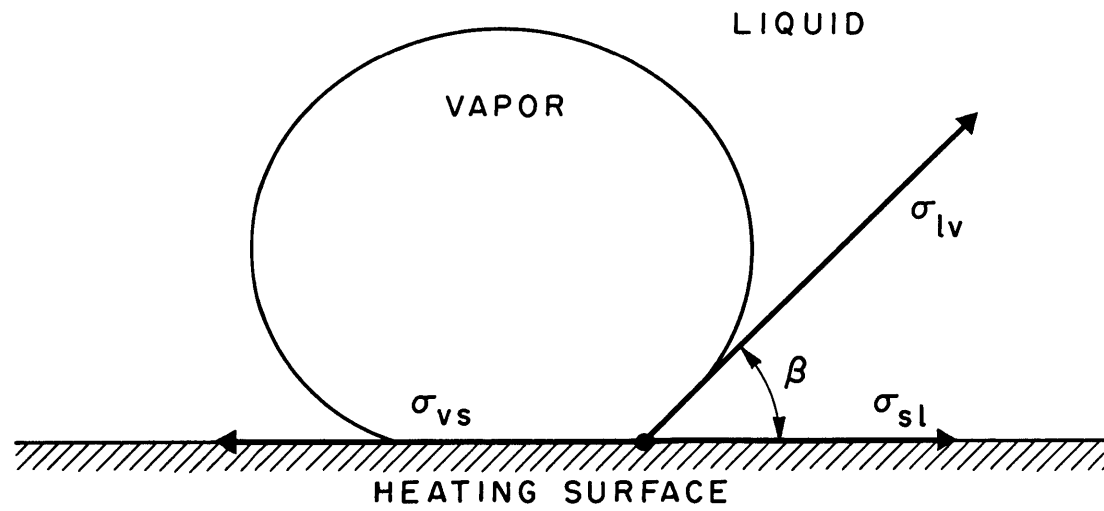


FIGURE 3

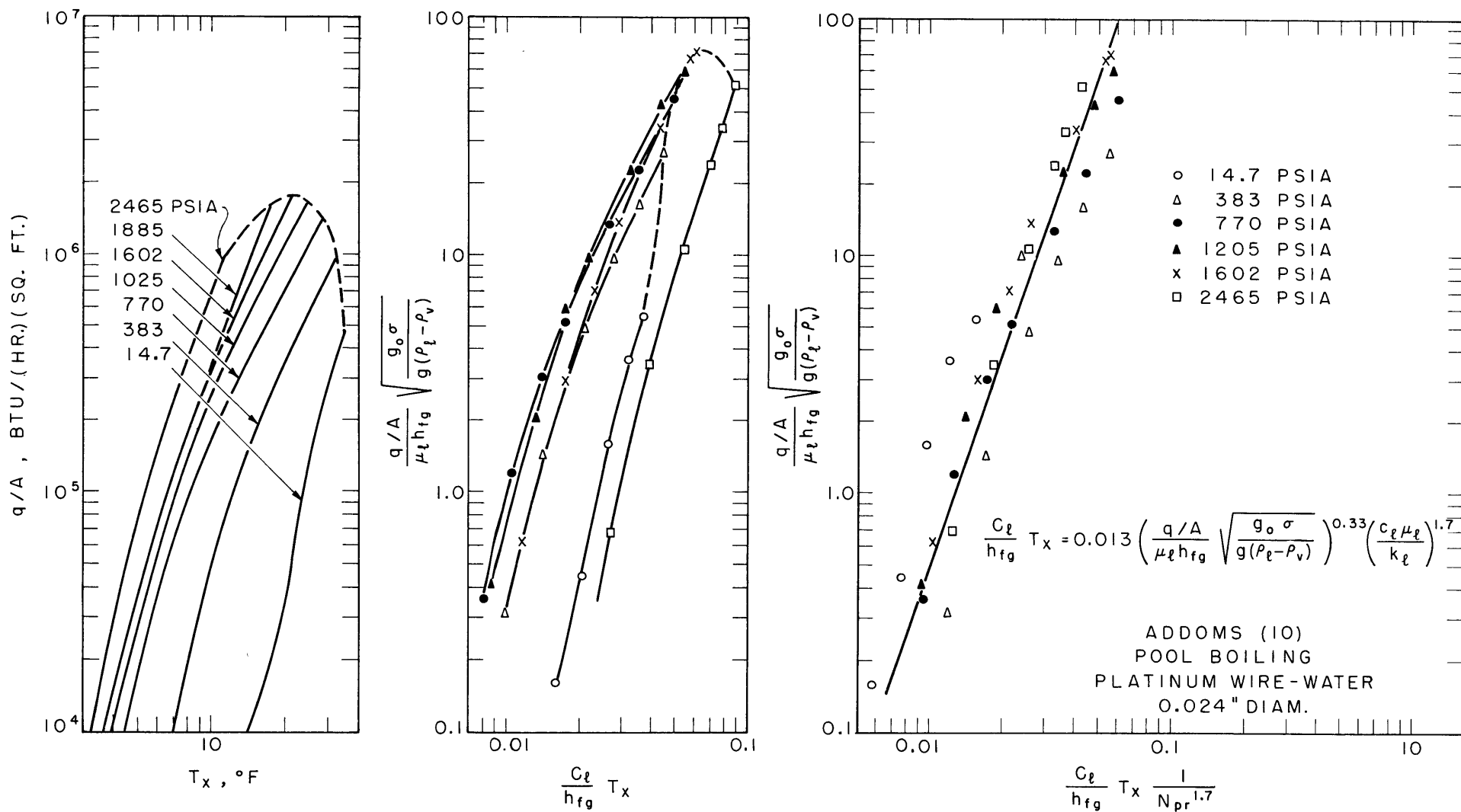


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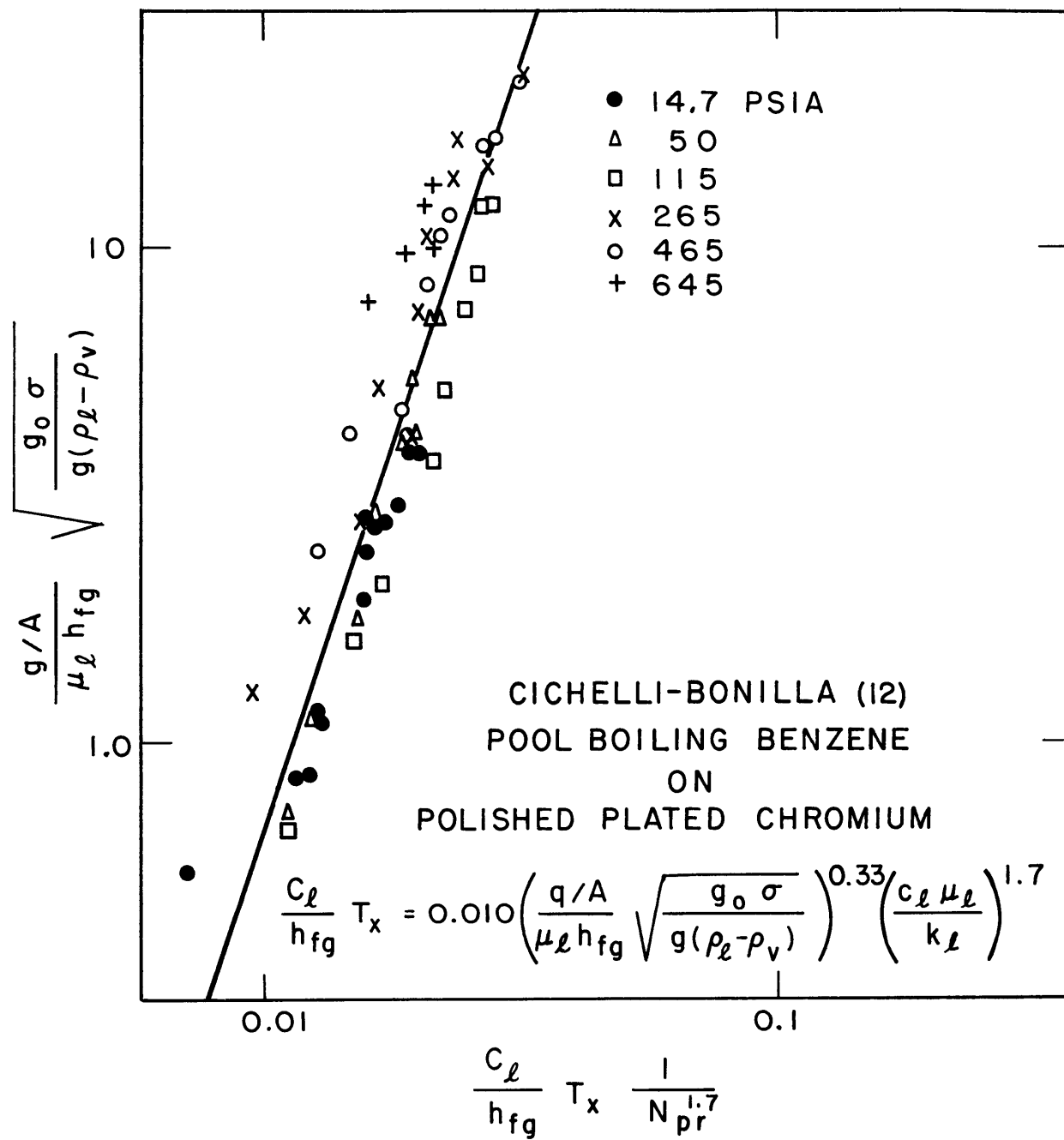


FIGURE 5

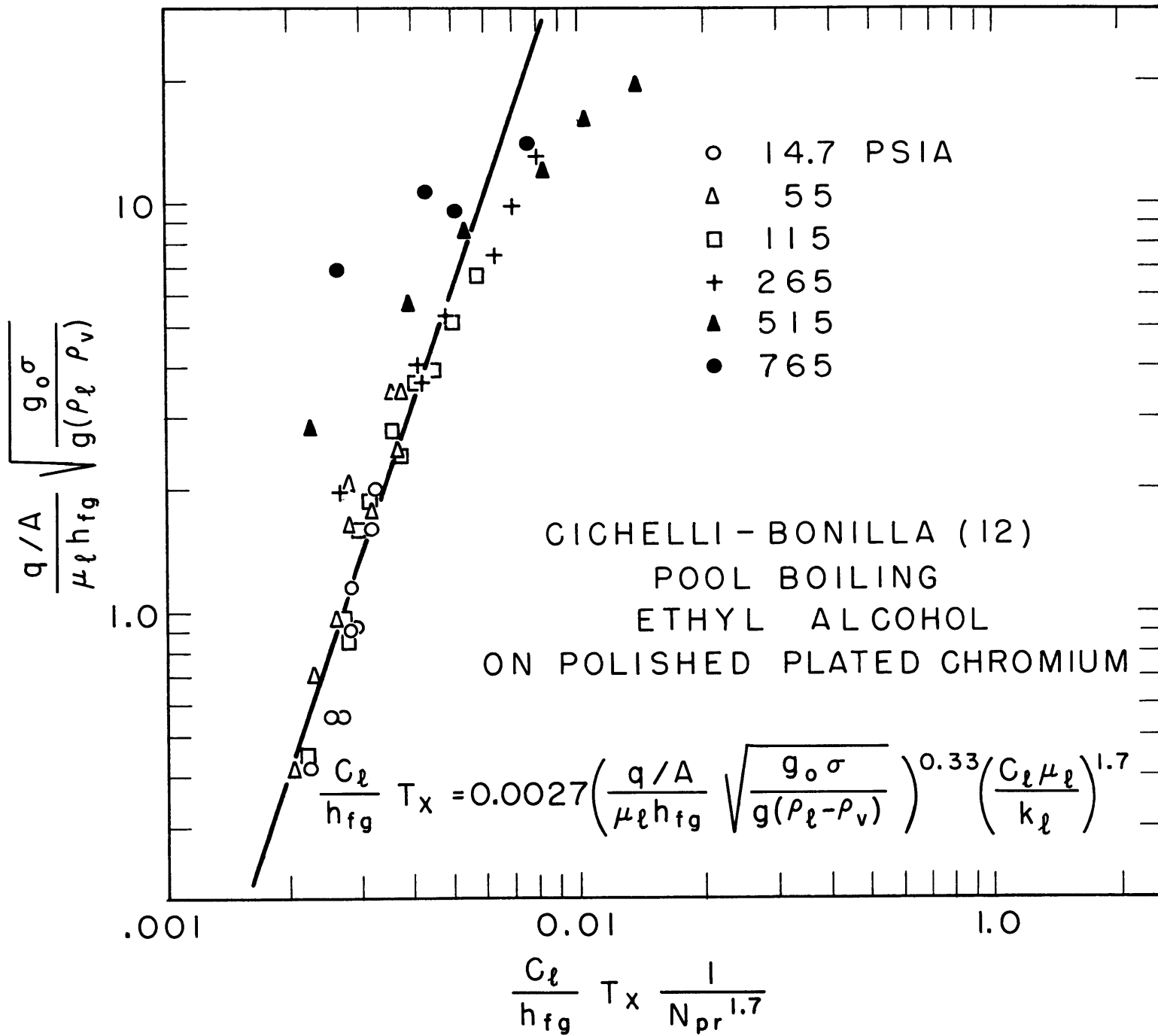


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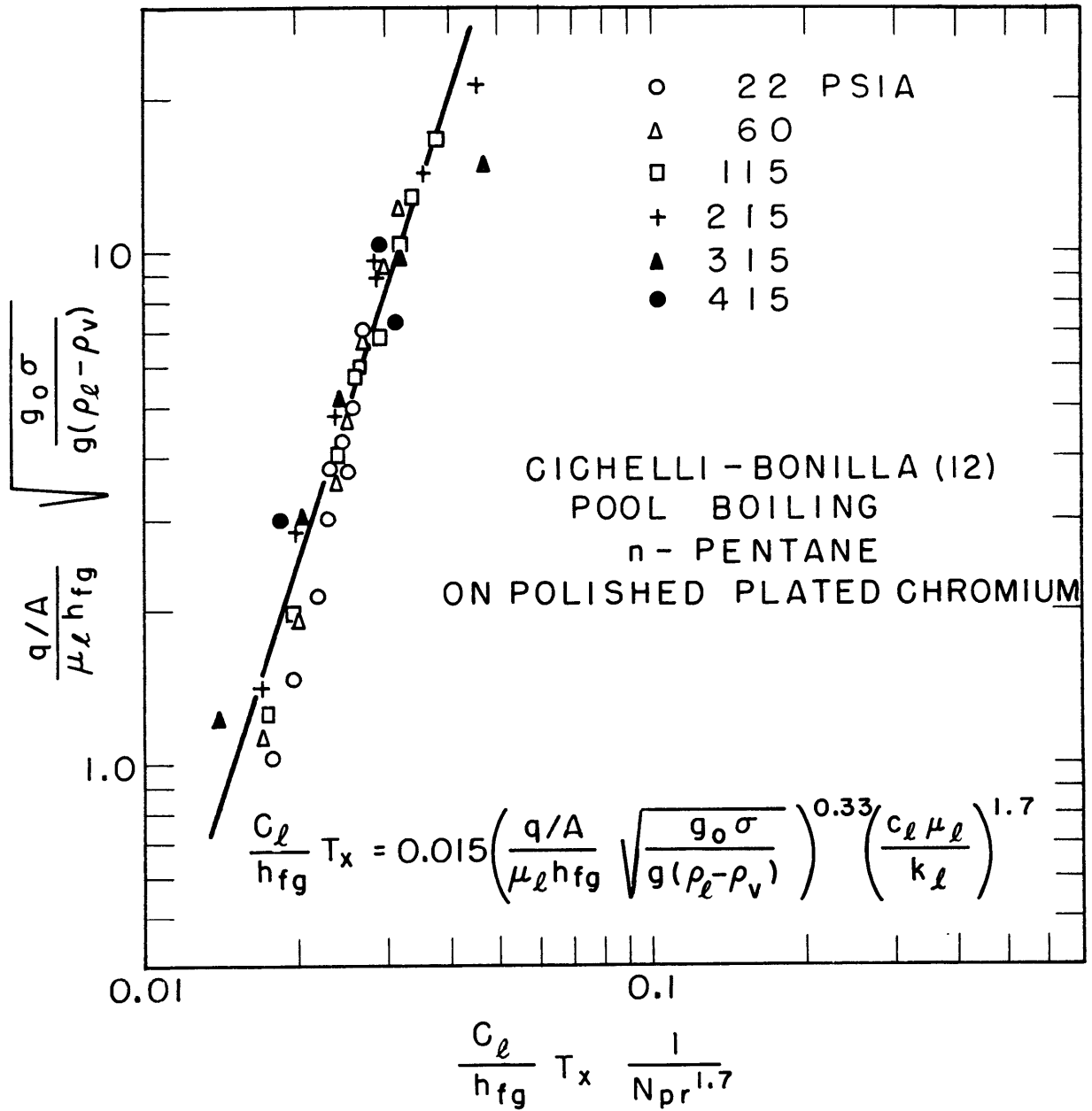


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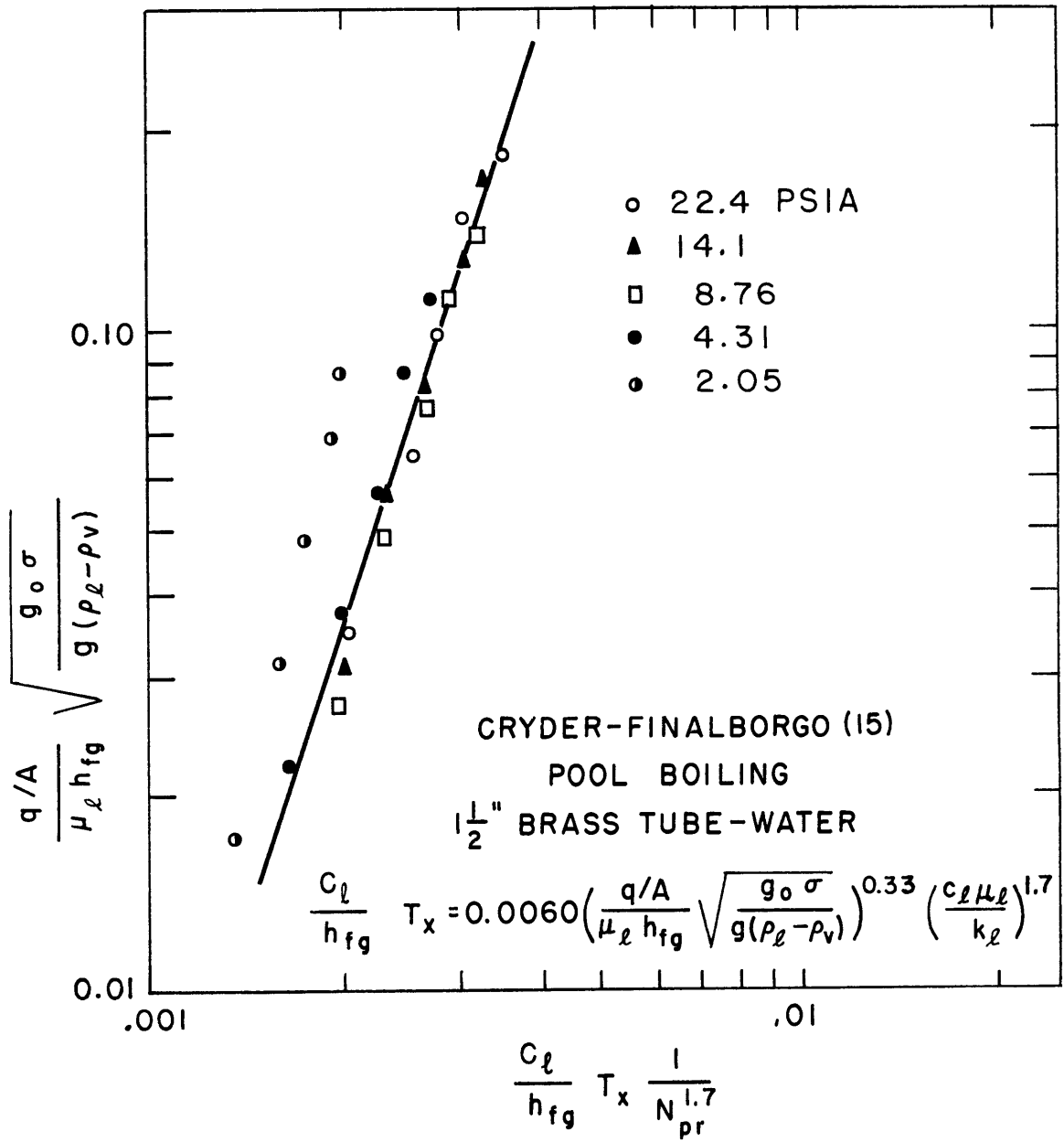


FIGURE 8

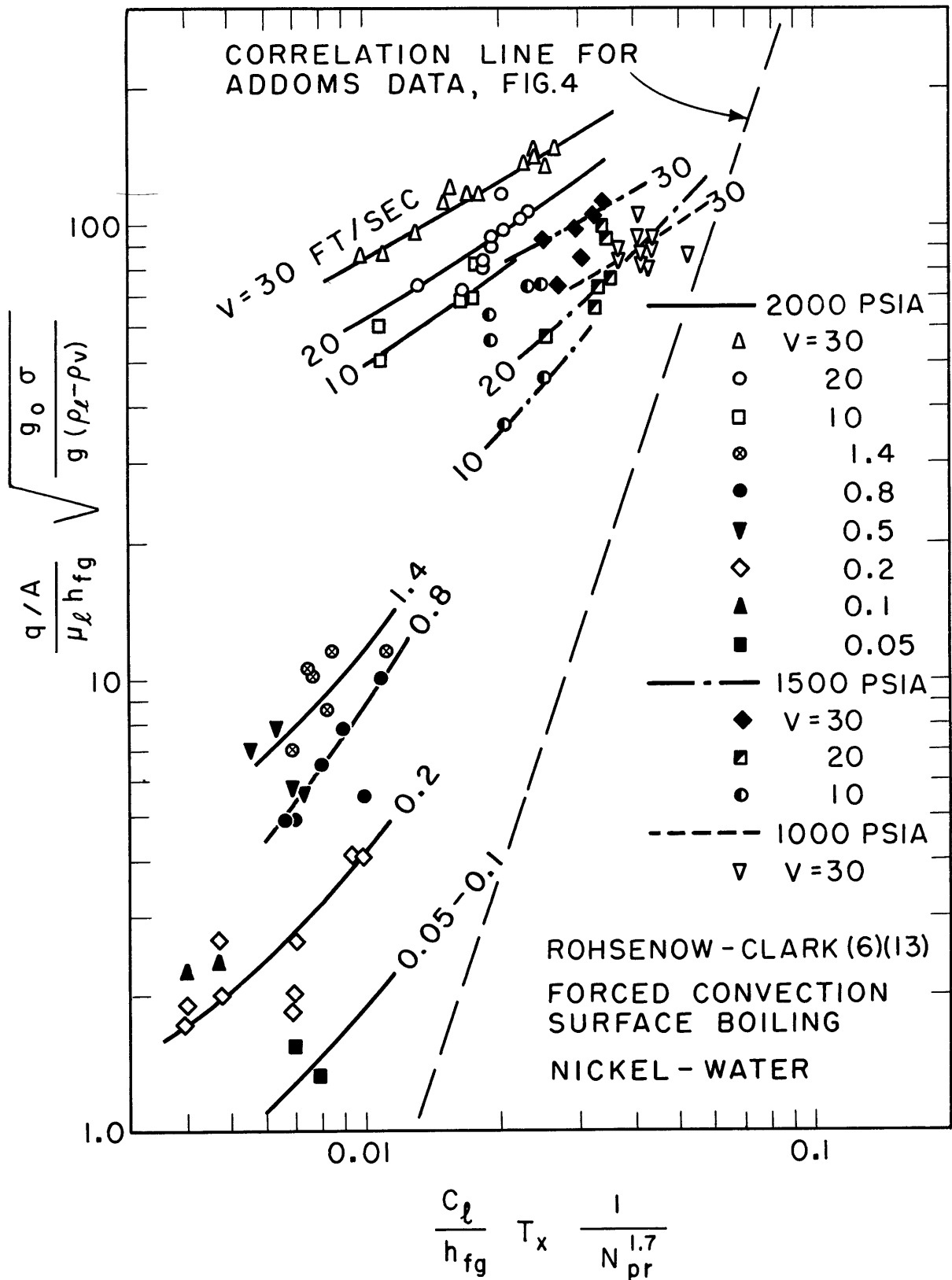


FIGURE 9

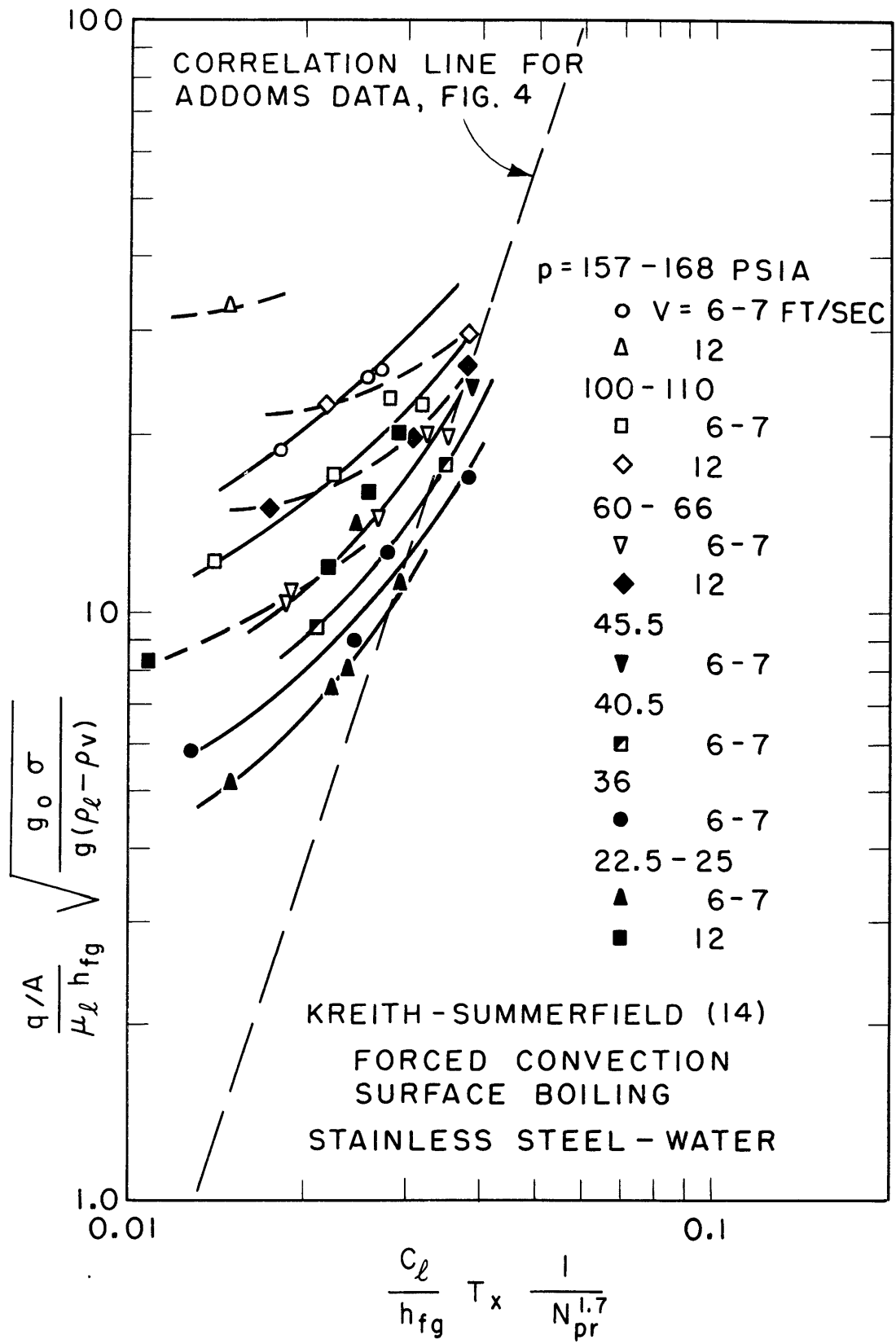


FIGURE 10

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