

A CORRELATION FOR BOILING HEAT TRANSFER
TO SATURATED FLUIDS IN CONVECTIVE FLOW

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ABSTRACT

An additive mechanism of micro- and macro-convective heat transfer was formulated to represent boiling heat transfer with net vapor generation to saturated, non-metallic fluids in convective flow. The final equations are:

$$h_{mic} = 0.00122 \frac{k_L^{0.79} C_{pL}^{0.45} \rho_L^{0.49} \Delta T^{0.24} \Delta P^{0.75} g_c^{0.25}}{\sigma^{0.5} \mu_L^{0.29} \lambda^{0.24} \rho_v^{0.24}} \times S$$

$$h_{mac} = 0.023 \frac{Pr_L^{0.4} Re_L^{0.8} k_L}{D} \times F$$

$$h = h_{mic} + h_{mac}$$

The second equation will be recognized as the Dittus-Boelter equation with the additional factor F. The two functions F and S are defined as

$$F = (Re/Re_L)^{0.8}$$

$$S = (\Delta T_e / \Delta t)^{0.99}$$

where Re is the effective Reynolds number for the two-phase fluid and ΔT_e is the effective superheat for bubble growth. F and S were obtained as functions of the Martinelli parameter and the two-phase Reynolds number, respectively.

The correlation was tested with available data for water and organic fluids. Data from different sources which could not be satisfactorily correlated by existing correlations were shown to be quite well correlated by the one presently proposed. The average deviation between calculated and measured boiling coefficients for all data points from nine experimental cases was $\pm 11\%$.

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Introduction

It has become almost a tradition that any paper dealing with the subject of boiling heat transfer should start by recognizing the complexity of the phenomenon. This complexity is especially evident in the case of convective boiling with net generation of vapor. Under these condition, the heat transfer is effected by the various flow parameters and the vapor quality as well as by the parameters which are pertinent in pool boiling. Figure 1a illustrates the wide range of local conditions and different flow regimes which could exist along the length of a boiler for such a case. Figure 1b illustrates typical fluid and wall temperature profiles corresponding to these various flow regimes. In the sub-cooled region, both the fluid and the wall temperatures increase as the liquid gains sensible heat. At the point where nucleate boiling starts, the wall temperature begins to decrease. The fluid temperature continues to increase until it reaches its saturation value, from which point on, it decreases gradually corresponding to the decreasing pressure. As the fluid progresses into the annular flow regime with continuously increasing vapor qualities, it is seen that the wall temperature decreases, reflecting an increasing heat transfer coefficient. This condition often exists into the fog-flow region. Finally, liquid deficiency occurs and there is a sudden decrease in the heat transfer coefficient with a corresponding rise in the wall temperature.

In view of the widely different conditions that could exist at various points along a boiler, it is this author's opinion that it would be entirely unprofitable either to measure over-all "average" coefficients or to attempt to correlate them. The only hope of obtaining results which can be

generalized is to work with local heat transfer coefficients. Furthermore, since the mechanisms of heat transfer may be different for the various flow regimes, it seems that any analytical study or correlation could be expected to apply strictly to only one of the possible flow regimes. It is therefore necessary that the region of applicability be clearly defined for a particular analytical study or correlation. The region of interest in this study is defined by the following conditions:

1. saturated, two-phase fluid in convective flow
2. vertical, axial flow
3. stable flow
4. no slug flow
5. no liquid deficiency
6. heat flux less than critical flux

These conditions usually occur with annular flow or annular-mist flow in the quality range of approximately 1 to 70%.

Background

There have been a number of experimental studies in this field reporting data on systems with water, organic fluids and even liquid metals. In this present analysis, we are concerned only with the first two classes of fluids. In some of these studies, the authors presented equations correlating their own data. In almost all such cases, it was implied that the correlations could be generalized to apply to other systems.

One of the first major works in this area was that of Dengler and Addoms [1] who in 1952 obtained local boiling coefficients for water in upward vertical flow through a one-inch tube. They proposed the following empirical correlation for their data.

[1] Numbers in parenthesis refer to numbered references in Bibliography.

$$h = 3.5 \frac{F_{DA}}{(x_{tt})^{0.5}} \times h'_L \quad (1)$$

where h'_L is evaluated by the conventional Dittus-Boelter equation.

$$h'_L = 0.023 \frac{k_L}{D} \left(\frac{DG}{\mu_L} \right)^{0.8} \left(\frac{C_{pL} \mu_L}{k_L} \right)^{0.4}$$

In the above correlation, F_{DA} represents the correction factor to be applied for points where nucleate boiling exists.

In 1956, Guerrieri and Talty [2] reported local boiling coefficients for a number of organic liquids in single-tube vertical boilers. They were able to correlate 88% of their data to within $\pm 20\%$ by the following equations.

$$h = 0.187 \left(\frac{r^*}{\delta} \right)^{-5/9} \times 3.4 \frac{h_L}{(x_{tt})^{0.45}}$$

$$h_L = (1-x)^{0.8} h'_L$$

(2)

$$r^* = \frac{2RT_s^2 \sigma}{P_s \lambda (T_w - T_s)}$$

$$\delta = \frac{10\mu_L}{\rho_L} \left[\frac{4\rho_L}{(dP/dL) Dg_c} \right]^{1/2}$$

In 1959, Bennett and co-workers [3] reported data for water flowing vertically in annular test sections. They compared their data with both the correlation of Dengler and Addoms and that of Guerrieri and Talty but, in each case, found considerable scatter. They then proposed their own correlation where

the local heat flux, q/A , was used as a multiplicative correction factor.

$$h = 0.64 \frac{1}{(X_{tt})^{0.74}} \times h_L \times \left(\frac{q}{A}\right)^{0.11} \quad (3)$$

In 1960, Sani [4] presented data for water in vertical flow through a tube. The author compared his results with the available correlations but found the deviations to be quite substantial. No new correlation was proposed.

In 1962, Schrock and Grossman [5] published a report on force-convective boiling of water in tubes. They introduced the boiling number, B_o , as an extra variable and obtained a correlation of the form,

$$h = 7,400 [B_o + 1.5 \times 10^{-4} \left(\frac{1}{X_{tt}}\right)^{2/3}] h_L' \quad (4)$$

$$B_o = \left(\frac{q}{A}\right) \left(\frac{1}{G\lambda}\right)$$

The authors reported that this equation correlated their data to within $\pm 35\%$. However, when Sani [4] compared his results with this correlation, he discovered that the experimentally measured coefficients were almost twice as great as those predicted.

There are a number of other correlations reported in the literature. Most of them, however, deal with either sub-cooled boiling or boiling with horizontal flow and therefore are irrelevant to the present study.

Comparison of Existing Correlations

From a literature survey as summarized above, there appeared to be a need for testing the various correlations against a representative body of available data. This was carried out

with the aid of a digital computer and some of the results are shown in Figures 2, 3, 4, and 5. In these figures the predicted values of the boiling coefficients have been plotted against the experimental values, the 45° line representing perfect correlation. Due to lack of space, only a representative fraction of the 564 data points used in this check have been shown in these figures. The range of experimental conditions covered by the data in this comparison are summarized in Table I. Figure 2 shows that while the correlation of Dengler and Addoms [1] represents the authors' own data fairly well, it predicts coefficients which are too high when compared with data from other sources. Figure 3 shows that the equation proposed by Guerrieri and Talty[2] correlates their own results quite well but predicts coefficients much lower than those measured by Dengler and Addoms and by Sani. This correlation, however, appears to predict coefficients of the right order of magnitude when compared with the data of Schrock and Grossman. Figure 4 shows that Bennett's [3] correlation appears to predict reasonable values for the majority of the water data although the scatter is quite great. However, the predicted coefficients are approximately 50% too low when compared with the organic data. In general, the correlation of Schrock and Grossman [5], as shown in Figure 5, appears to be better than the other three. With respect to the organic data, this correlation gives values which are approximately 30% too low. The correlation does appear to bisect the water data although the scatter ranges from a +30% to -50%.

In general, it appears that none of the correlations is entirely satisfactory for general use. Indications are that the pertinent variables have not been correctly accounted for in these correlations.

Derivation of Equations

It is postulated that there are two basic mechanisms which take part in the heat transfer process for the boiling of saturated fluids with flow. These are (1) the ordinary macro-convective mechanism of heat transfer which normally operates with flowing fluids, and (2) the micro-convective mechanism associated with bubble-nucleation and growth. It is further postulated that these two mechanisms are additive in their contributions to total heat transfer. The concept of additive contributions is not new. Rohsenow [6] in 1952 first suggested that the heat transfer associated with convection and with boiling can be added. Gambill [7] recently applied the additive concept to correlate boiling burnout data. In both of these cases, sub-cooled nucleate boiling was treated, and the authors found that the convective and the boiling contributions could be super-imposed without modifications. In this present study, we are interested in saturated boiling with net vapor generation, and it is felt that for this case the two mechanisms would not have their normal effects but would be modified by effects of quality and by the interaction of one mechanism on the other. Under this general premise, equations describing these two mechanisms were formulated as follows.

Considering first the macro-convective mechanism, it was recognized that at the two limits of 0% and 100% quality, the macro-convective heat transfer should be described by the Dittus-Boelter type of correlation. It was then postulated that in the two-phase region where there are both liquid and vapor present, the macro-convective heat transfer should still be described by a modified form of the Dittus-Boelter equation.

$$h_{\text{mac}} = 0.023 (\text{Re})^{0.8} (\text{Pr})^{0.4} \frac{k}{D} \quad (5)$$

In this equation, the Prandtl and the Reynolds numbers and the thermal conductivity represent effective values associated with the two-phase fluid. We may define three parameters as ratios of these quantities divided by the liquid quantities.

$$\beta = \text{Pr}/\text{Pr}_L \quad (6)$$

$$\gamma = k/k_L \quad (7)$$

$$F = (\text{Re}/\text{Re}_L)^{0.8} = (\text{Re} \times \frac{u_L}{DGz})^{0.8} \quad (8)$$

In the case of ordinary fluids, i.e., not liquid metals, the Prandtl numbers of the liquid and of the vapor are normally of the same magnitude. The Prandtl number of the two-phase fluid should therefore also be of the same magnitude. Furthermore, since the heat is transferred through an annular film of liquid adhering to the wall, it is expected that the liquid properties would have the dominant effect. For these reasons it is reasonable to assume that β and γ may be taken to be unity as a first approximation. Eq. (5) may then be re-written as

$$h_{\text{mac}} = 0.023 (\text{Re}_L)^{0.8} (\text{Pr}_L)^{0.4} \frac{k_L}{D} F \quad (9)$$

The only unknown function in Eq. (9) is F , the ratio of the two-phase Reynolds number to the liquid Reynolds number, based on the liquid fraction of the flow. This ratio is strictly a flow parameter; and therefore by analogy to momentum transfer in two-phase flow, it may be assumed that F is a function of the Martinelli parameter X_{tt} . This postulate has been verified and the actual dependence of F on X_{tt} obtained by comparison with experimental data.

The analysis of Forster and Zuber [8] was taken as a basis for the formulation of a micro-convective mechanism of heat

transfer. The Forster and Zuber analysis was derived for the case of pool boiling and resulted in the following equation for the boiling Nusselt number.

$$\text{Nu}_b = 0.0015 (\text{Re}_b)^{0.62} (\text{Pr}_L)^{0.33} = \frac{h_b r_b}{k_L}$$

$$r_b = \frac{\Delta T}{\lambda \rho_v} \left(\frac{2\pi k_L \rho_L C_{pL} \sigma}{\Delta P} \right)^{0.5} \left(\frac{\rho_L}{g_c \Delta P} \right)^{0.25} \quad (10)$$

$$\text{Re}_b = \frac{\pi k_L C_{pL}}{\mu_L} \left(\frac{\rho_L \Delta T}{\rho_v \lambda} \right)^2$$

These equations are based on the premise that the Reynolds number for micro-convective boiling heat transfer is governed by the growth rate of bubbles. This rate is described by the Rayleigh equation which Forster and Zuber solved to show that the product of the bubble radius and the bubble growth rate is a constant for a specific superheat.

$$r_b \frac{dr_b}{d\theta} = \frac{\pi k_L \rho_L C_{pL}}{(\lambda \rho_v)^2} (\Delta T)^2 \quad (11)$$

As illustrated in Fig. 6 for the case of boiling from a superheated wall, whether in pool boiling or convective boiling, the degree of superheat actually is not constant across the boundary layer. Due to this fact, the Reynolds number used in the Forster-Zuber equation actually is an effective Reynolds number representative of some mean, effective superheat. The difference between this effective superheat and the wall superheat is small for the case of pool boiling and was neglected in Forster and Zuber's derivation. However, this difference cannot be neglected in the case of convective boiling since the temperature gradient is now dependent on flow rate

and vapor quality and would generally be much steeper than in the corresponding pool boiling case with the same wall superheat.

In using Forster and Zuber's formulation to represent micro-convective heat transfer in convective boiling, this effect was taken into account by writing Eq. (10) in terms of effective ΔT and ΔP .

$$h_{mic} = 0.00122 \frac{k_L^{0.79} C_{pL}^{0.45} \rho_L^{0.49} g_c^{0.25}}{\sigma^{0.5} \mu_L^{0.29} \lambda^{0.24} \rho_v^{0.24}} (\Delta T_e)^{0.24} (\Delta P_e)^{0.75} \quad (12)$$

Then a suppression factor, S , was defined as the ratio of the effective superheat to the total superheat of the wall

$$S = \left(\frac{\Delta T_e}{\pi T} \right)^{0.99} \quad (13)$$

The ratio is arbitrarily taken to the 0.99 power in order that S would appear to the first power in the final equations.

By the Clausius and Clapeyron equation,

$$(\Delta T_e)^{0.99} = \left(\frac{T_e}{\lambda \rho_v j} \right)_{T_e}^{0.75} (\Delta T_e)^{0.24} (\Delta P)^{0.75}$$

$$(\Delta T)^{0.99} = \left(\frac{T}{\lambda \rho_v j} \right)_T^{0.75} (\Delta T)^{0.24} (\Delta P)^{0.75} \quad (14)$$

For $\frac{\Delta T}{T} \ll 1$, we can write,

$$\left(\frac{T_e}{\lambda \rho_v j} \right)_{T_e} \cong \left(\frac{T}{\lambda \rho_v j} \right)_T \quad (15)$$

and,

$$S = \left(\frac{\Delta T_e}{\Delta T} \right)^{0.24} \left(\frac{\Delta P_e}{\Delta P} \right)^{0.75} \quad (16)$$

Combining with Eq. (12), we then obtain an expression for the micro-convective coefficient in terms of the suppression factor and the total superheat.

$$h_{mic} = 0.00122 \frac{k_L^{0.79} C_{pL}^{0.45} \rho_L^{0.49} g_c^{0.25}}{\sigma^{0.5} \mu_L^{0.29} \lambda^{0.24} \rho_v^{0.24}} (\Delta T)^{0.24} (\Delta P)^{0.75} S \quad (17)$$

The suppression factor, S , approaches unity at zero flow rate and zero at infinite flow rate. It was postulated, subject to experimental verification, that in all ranges of flow S can be represented as a function of the local two-phase Reynolds number.

The total heat transfer coefficient is then obtained as the sum

$$h = h_{mic} + h_{mac} \quad (18)$$

The two unknowns in the above equations are the Reynolds number factor, F , and the suppression factor, S . These two functions were determined empirically from experimental data by the following procedure.

A first estimate of F was obtained by plotting the ratio of experimental two-phase heat transfer coefficient divided by the liquid coefficient as a function of the reciprocal Martinelli parameter. Using this estimate of F , values of h_{mic} were obtained from Eq. (17) and (18) by subtracting the estimated values of h_{mac} from the experimental data. The results were then plotted against two-phase Reynolds number and a best-fit curve was obtained for S . Using this first estimate of the S function, a second estimate of F was calculated from the experimental data and compared with the original estimate of F . This iterative procedure was repeated for a total of ten trials, at the end of which, the two functions were found to remain relatively constant from one trial to the next and were

assumed to have converged. In this procedure, only data from experiments with substantial macro-convective heat transfer were used to correlate the F function, and only data from experiments with substantial micro-convective heat transfer were used to correlate the S function. This selective weighting of the data served to increase precision in the determination of the two functions. The results are shown in Figs. 7 and 8. The shaded areas on these two plots represent the scatter of the data around the two correlating functions. It is seen that F increases with increasing values of the reciprocal Martinelli parameter, indicating that the effective turbulence associated with two-phase flow increases with increasing vapor fraction. The suppression factor, S , is seen to approach unity at low values of the two-phase Reynolds number and decrease asymptotically to zero at high values of the two-phase Reynolds number. These results are reasonable in indicating that at low flow rates and low fraction vapor the boiling mechanism plays a relatively important part, whereas at high flow rates and high fraction vapor, the boiling is suppressed and the macro-convective heat transfer mechanism becomes increasingly important.

The final correlation is given by Eqs. (9), (17), and (18) with the two correlating functions, F and S , represented graphically in Figs. 7 and 8.

Comparison with experimental data

This correlation was tested against available data for both water and organic fluids. The comparisons are shown in Figs. 9 and 10. It is seen that this correlation fits the data from all, rather than from just one or two, of the sources. It also reduces the scatter quite substantially. The points presented in Fig. 9 include data for water, methanol, cyclohexane,

and pentane. The mechanism and resulting equations postulated above appear to correlate all these data quite well. The average deviation for Dengler and Addoms' water data was 14.7%; for Schrock and Grossman's water data, 15.1%; for Guerrieri and Talty's methanol data, 11.3%; for their cyclohexane data, 13.6%; and for their pentane data, 11.9%. It is interesting to note that one of the sets best correlated by this formulation is the data of Sani for water in downflow through a tube. The deviation for this set of data is only 8.5%. This indicates that for the range of flow conditions encountered, the direction of vertical flow makes no appreciable difference. Previously, there was some uncertainty on this question since Schrock and Grossman had not been able to demonstrate consistency between their upflow results and Sani's downflow results.

Figure 10 shows further comparisons of this correlation with experimental results. Results for benzene and heptane are presented here along with results for water taken by Bennett et al. It is interesting to note that Bennett's data can also be correlated by this formulation in view of the fact that his coefficients were obtained on annuli whereas the other data were all obtained on round tubes. The equivalent diameter used to correlate Bennett's annular data was four times the cross sectional area divided by the heated perimeter. The average deviations for Bennett's water data and for the benzene and heptane data of Guerrieri and Talty are 10.8%, 6.3%, and 11.0% respectively.

Another method of testing this correlation is to see if it can predict correctly the wall temperature profile along the length of a boiler when all other conditions are given. Some results from such tests are shown in Fig. 11. Part (a)

shows a comparison with data from one of Schrock and Grossman's runs in which the incoming liquid was sub-cooled. It is seen that for the initial lengths of the boiler, the measured wall temperatures diverge from the calculated values. However, for later lengths of the boiler where vapor quality becomes greater than 2% and annular flow could exist, the calculated wall temperatures are seen to be verified by the experimental measurements. Part (b) of the same figure shows results of a comparison with data from one of Sani's runs. In this case, the fluid entered with 7% vapor quality, and annular flow likely existed through the entire length of the boiler. It is seen that the calculated and measured wall temperatures are in good agreement.

It is also of interest to see if this correlation can correctly predict the variation of the ratio h/h_L with Martinelli parameter X_{tt} . The majority of data available in the literature are presented as plots of h/h_L vs. $1/X_{tt}$. Many investigators [2], [3], [5] have found that at high values of $1/X_{tt}$, the data converge to a single line; whereas at low values of $1/X_{tt}$, the data seem to diverge in parameter curves. This divergence has not been satisfactorily reproduced by any of the previous theoretical equations. Fig. 12 shows curves of h/h_L calculated by this correlation. It is seen that these calculated curves do show the characteristic divergence at low values of $1/X_{tt}$ and, in fact, when compared with experimental data for identical conditions (Curve 2), excellent agreement is obtained. Furthermore, the above analysis indicates that at high values of $1/X_{tt}$ the ratio h/h_L should converge to the ratio $(Re/Re_L)^{0.8}$, i.e., the F function.

Table I lists the range of experimental conditions covered by the data which were used in the various comparisons above. Table II summarizes the average deviations for this

and for the other correlations when tested against these data. It is seen that the combined average deviation for this correlation is $\pm 11\%$, approximately one-third the deviations for the other correlations. Thus it appears that for the range of conditions listed in Table I, this correlation markedly improves the chances of accurately predicting two-phase boiling coefficients.

Summary

The case of boiling heat transfer to saturated, ordinary fluids in convective flow was treated in this study with the hope of developing a method for predicting the heat transfer coefficients. For the regime of annular or annular mist-flow, it was postulated that the total heat transfer is comprised of contributions from micro-convective and macro-convective mechanisms. The micro-convective contribution to heat transfer was then derived from the Forster and Zuber correlation for pool boiling heat transfer. A Dittus-Boelter type of equation was formulated to account for the macro-convective contribution. In these formulations, two dimensionless functions, S and F , were proposed to account for the suppression of nucleate boiling by the forced convective flow and for the increase in turbulence due to two-phase flow. These two correlating functions were determined empirically from available data and are presented graphically.

Using this correlation, it was shown that the wall temperature profile along a boiler and the curves of h/h_L vs. $1/X_{tt}$ can be predicted correctly. In testing this correlation against all pertinent data from nine experimental cases reported in the literature for both water and organic fluids, the average deviation was found to be $\pm 11\%$. This is a substantial improvement over existing correlations.

This correlation is recommended for use in predicting boiling heat transfer coefficients for saturated, non-metallic fluids in convective flow. While the same type of mechanism is expected to apply also to boiling liquid metals, the specific correlation presented here would not be applicable without modification. For water and organics it is expected to be applicable in the quality range of approximately 1 to 70% vapor.

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TABLE I

Range of Conditions for Data Used in Testing Correlation

Reference	Fluid	Geometry	Flow	Pressure (psia)	Flow Vel. (ft/sec liq.)	Quality (wt.%)	$Q/A \times 10^{-4}$ (Btu)/(hr) (ft ²)
1	water	tube	up	8- 40	0.2-4.8	15-71	2.8-20
5	water	tube	up	42-505	0.8-14.7	3-50	6.5-76
4	water	tube	down	16- 31	0.8-2.7	2-14	1.4-5.0
3	water	annulus	up	15- 35	0.2-0.9	1-59	3.2-16
2	methanol	tube	up	15	1.0-2.5	1-4	0.7-1.7
2	cyclohexane	tube	up	15	1.3-2.8	2-10	0.3-1.3
2	pentane	tube	up	15	0.9-2.2	2-12	0.3-1.2
2	heptane	tube	up	15	1.0-2.4	2-10	0.2-0.9
2	benzene	tube	up	15	1.0-2.4	2-9	0.4-1.3

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TABLE II
Comparison of Correlations

<u>Data</u>	<u>Average Percent Deviations for Correlations</u>				
	<u>Dengler & Addoms</u>	<u>Guerrieri & Talty</u>	<u>Bennett et al.</u>	<u>Schrock & Grossman</u>	<u>This Correlation</u>
Dengler & Addoms (water)	30.5	62.3	20.0	20.3	14.7
Schrock & Grossman (water)	89.5	16.4	24.9	20.0	15.1
Sani (water)	26.9	70.3	26.5	48.6	8.5
Bennett et al. (water)	17.9	61.8	11.9	14.6	10.8
Guerrieri & Talty (methanol)	42.5	9.5	64.8	62.5	11.3
Guerrieri & Talty (cyclohexane)	39.8	11.1	65.9	50.7	13.6
Guerrieri & Talty (benzene)	65.1	8.6	56.4	40.1	6.3
Guerrieri & Talty (heptane)	61.2	12.3	58.0	31.8	11.0
Guerrieri & Talty (pentane)	66.6	9.4	59.2	35.8	11.9
Combined average for all data	38.1	42.6	32.6	31.7	11.0

Nomenclature

B_o	boiling number, $\frac{q/A}{\lambda G}$
C_p	heat capacity, (Btu)/(Lb) (°F)
D	diameter, (Ft)
dP/dL	pressure drop along boiler, (psf)/(Ft)
F	Reynolds number factor, $(Re/Re_L)^{0.8}$
F_{DA}	Dengler and Addoms' correction factor, see Eq. (1)
G	mass flow velocity, (Lb)/(Hr) (Ft ²)
g_c	gravitational constant
h	two-phase heat transfer coefficient, (Btu)/(Hr) (Ft ²) (°F)
h'_L	total liquid heat transfer coefficient, see Eq. (1)
h_L	fraction liquid heat transfer coefficient, see Eq. (2)
j	Joule's constant, 778 (Ft) (Lb)/(Btu)
k	thermal conductivity, (Btu)/(Hr) (Ft) (°F)
Nu_b	Nusselt number for bubble, see Eq. (10)
P	pressure (psf)
Pr	Prandtl number
q/A	heat flux, (Btu) (Hr) (Ft ²)
r_b	radius of bubble, see Eq. (10)
Re	effective Reynolds number for two-phase fluid
Re_b	Reynolds number for bubble
Re_L	Reynolds number for liquid fraction
S	suppression factor, $(\Delta T_e/\Delta T)^{0.99}$
T	temperature, (°R)
x	weight fraction vapor
X_{tt}	Martinelli parameter, $(\frac{z}{x})^{0.9} (\frac{\rho_v}{\rho_L})^{0.5} (\frac{\mu_L}{\mu_v})^{0.1}$
z	weight fraction liquid

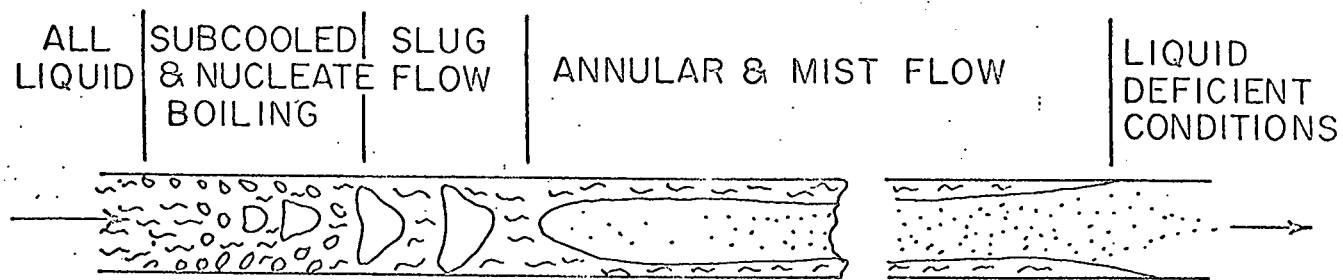
β	Pr/Pr_L
γ	k/k_L
ΔP	difference in vapor pressure corresponding to ΔT , (Psf)
ΔT	superheat, $T_w - T_s$
ΔT_e	effective superheat with flow, see Eq. (13)
λ	latent heat of vaporization, (Btu)/(Lb)
μ	viscosity, (Lb)/(Ft) (Hr)
ρ	density, (Lb)/(Ft ³)
σ	vapor-liquid surface tension, (Lb)/(Ft)

Subscripts:

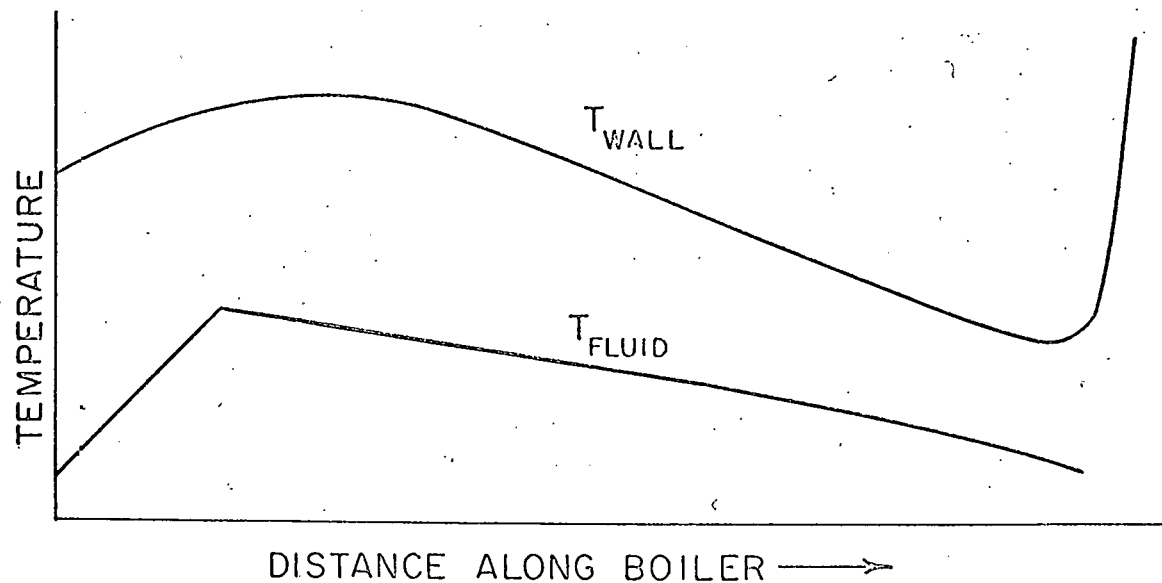
none	value for two-phase fluid
e	effective value with flow
L	value for liquid
s	value at saturation condition
v	value for vapor
w	value at wall condition

Captions for Illustrations

- Figure 1 Conditions Along Boiler
(a) Flow Regimes
(b) Longitudinal Temperature Profiles
- Figure 2 Comparison of Correlation of Dengler and Addoms with Experimental Results from Various Sources
- Figure 3 Comparison of Correlation of Guerrieri and Talty with Experimental Results from Various Sources
- Figure 4 Comparison of Correlation of Bennett et al. with Experimental Results from Various Sources
- Figure 5 Comparison of Correlation of Schrock and Grossman with Experimental Results from Various Sources
- Figure 6 Temperature Profiles for Pool Boiling and for Convective Boiling with the Same Total Superheat
- Figure 7 Reynolds Number Factor, F
- Figure 8 Suppression Factor, S
- Figure 9 Comparison of this Correlation with Experimental Results from Various Sources
- Figure 10 Further Comparison of this Correlation with Experimental Results from Various Sources
- Figure 11 Comparison of Calculated and Measured Wall Temperatures
(a) Data of Schrock and Grossman
(b) Data of Sani
- Figure 12 Calculated and Measured Ratios of h/h_L as Functions of the Martinelli Parameter



(A) FLOW REGIMES



(B) LONGITUDINAL TEMPERATURE PROFILES

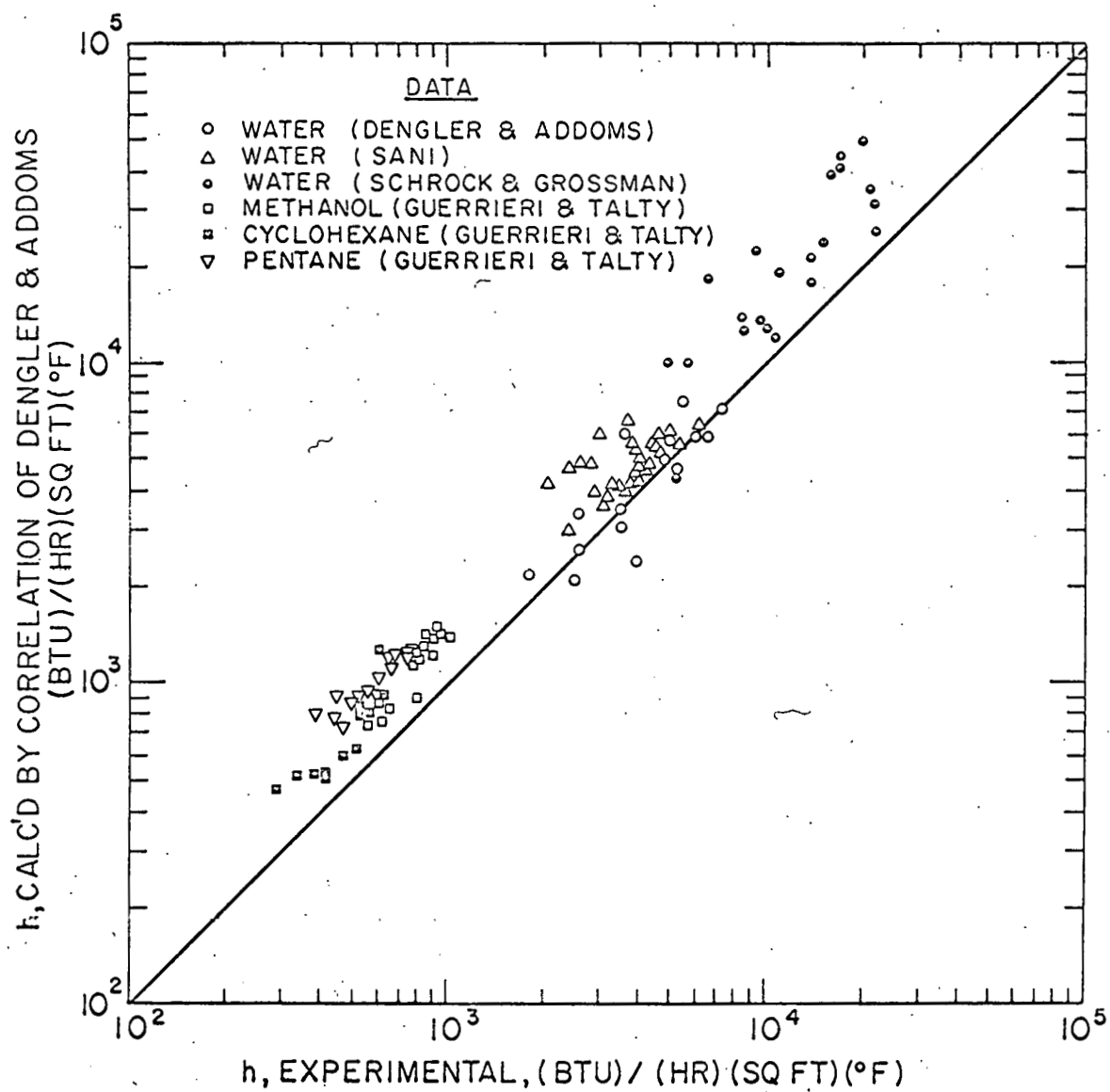
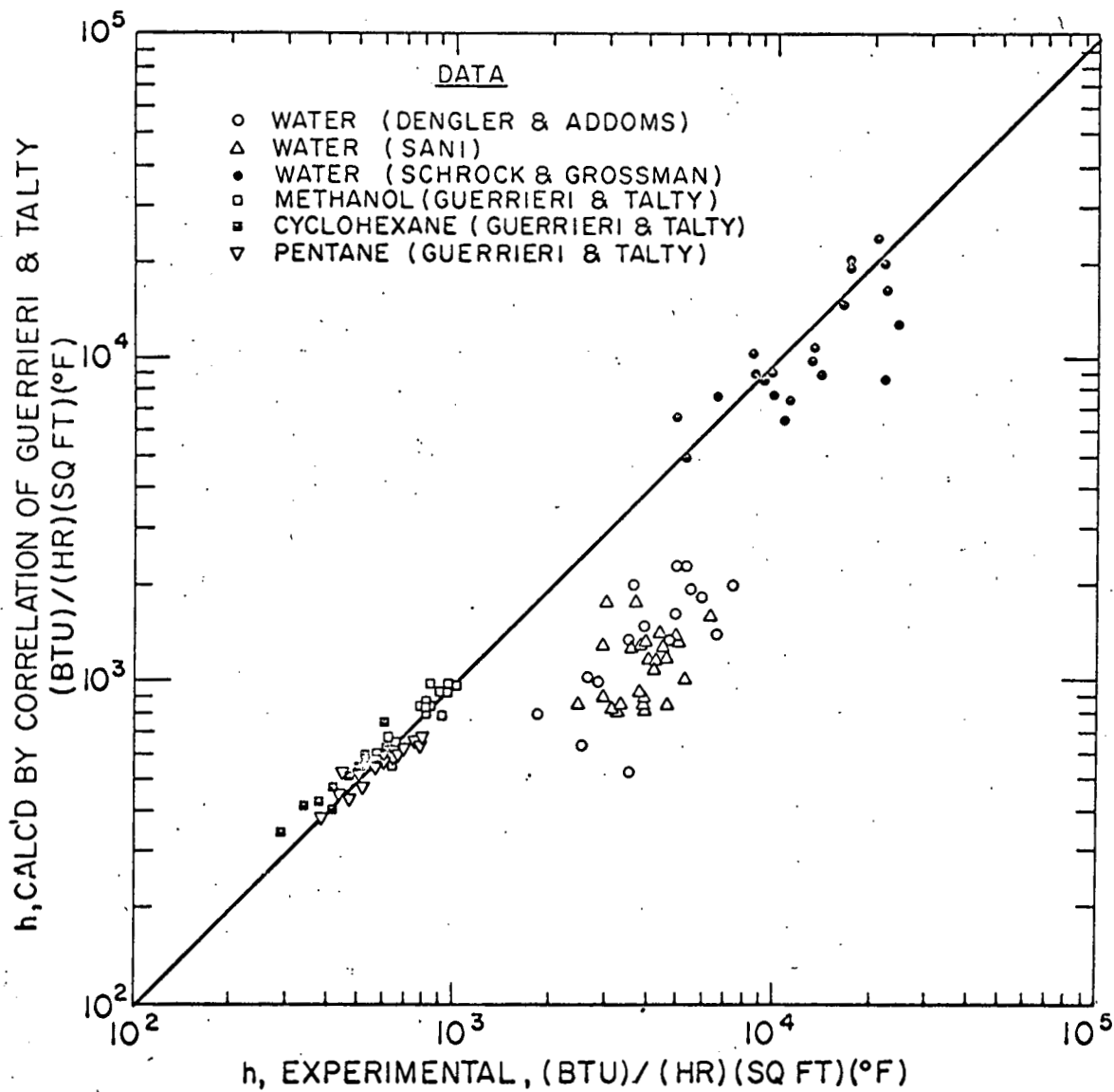
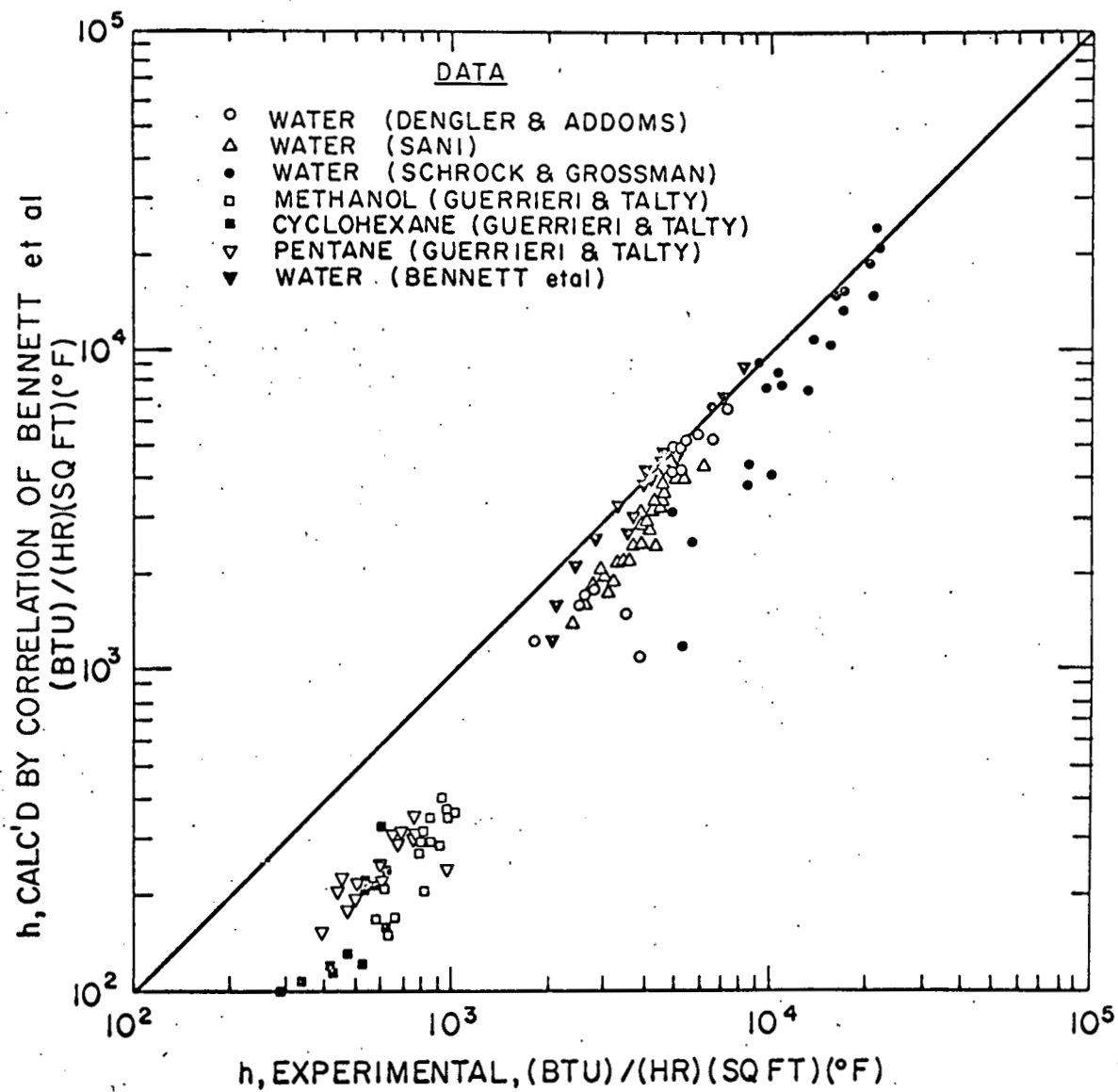


Fig. 2
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Fig. 4

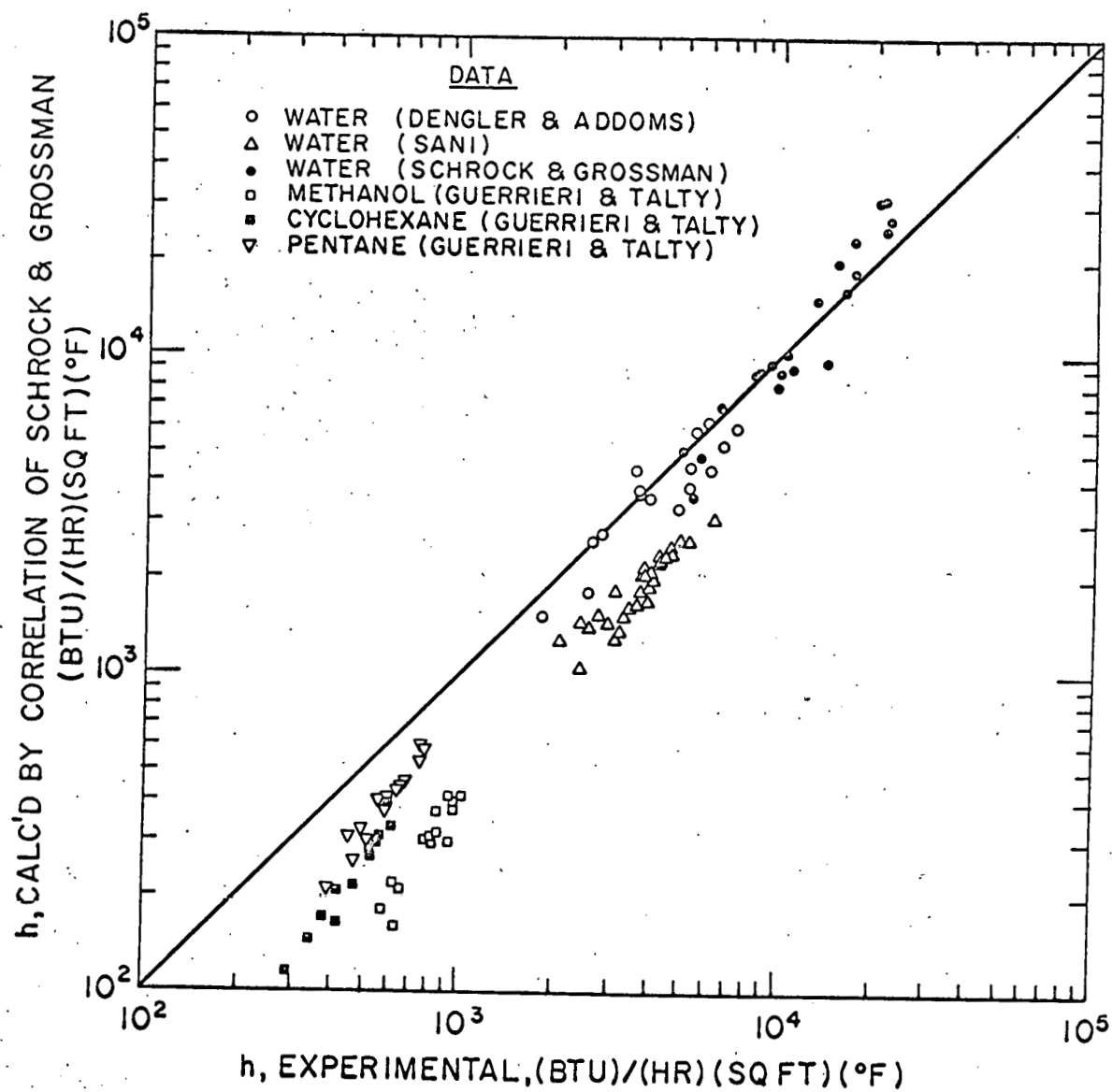


Fig. 5
J. C. Chen

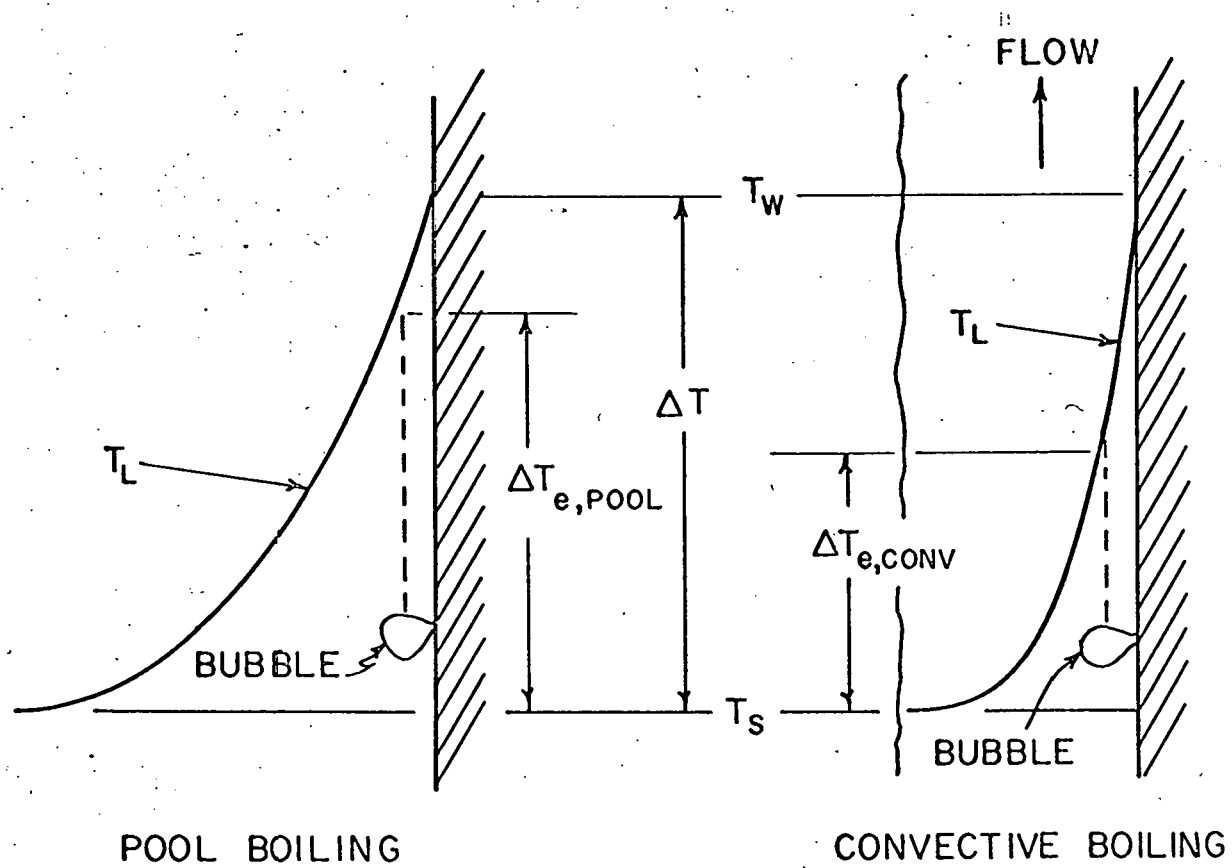
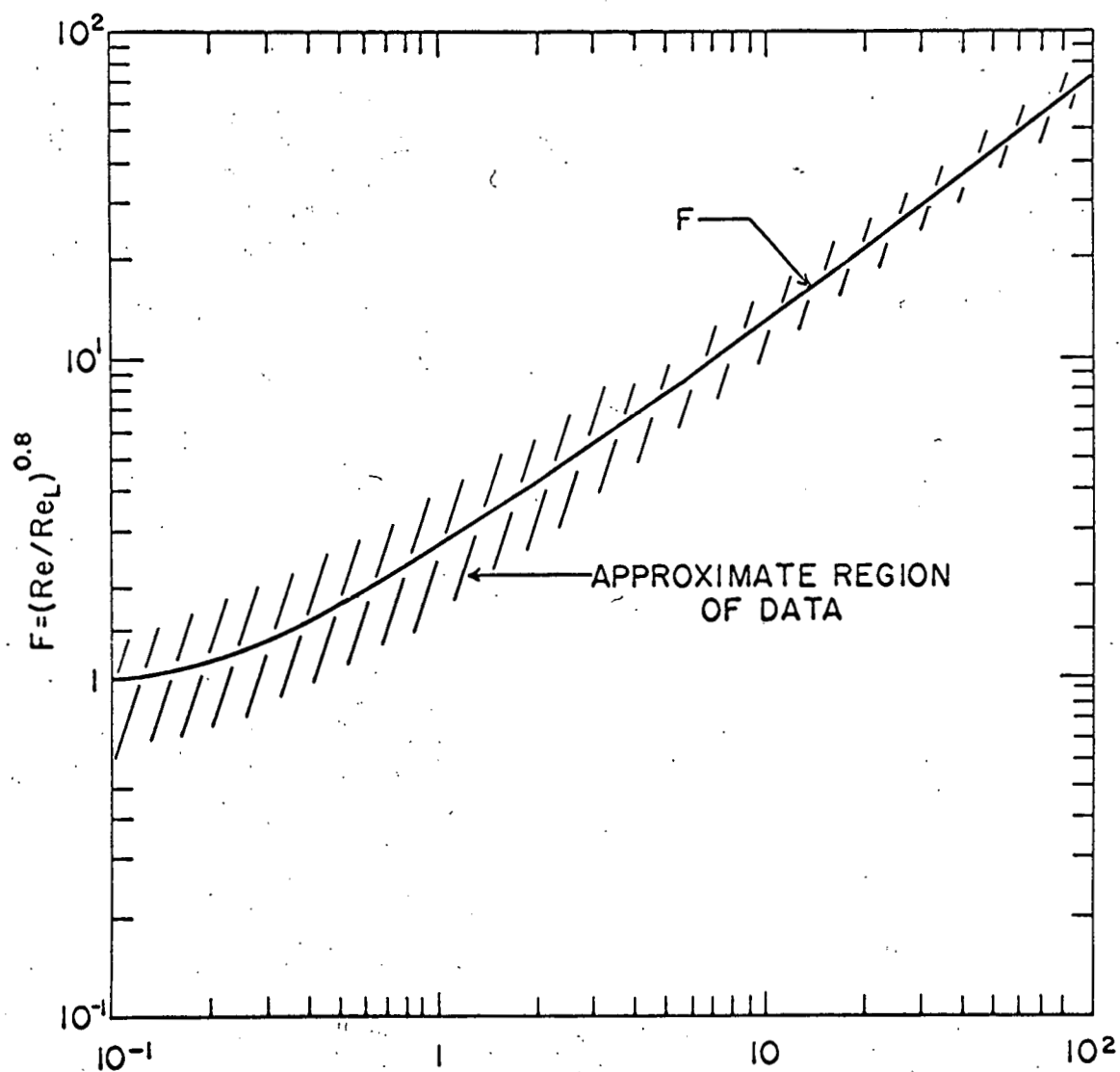


Fig. 6
J. C. Chen



$$\frac{1}{X_{tt}} = \left(\frac{X}{Z}\right)^{0.9} \left(\frac{\rho_L}{\rho_v}\right)^{0.5} \left(\frac{\mu_v}{\mu_L}\right)^{0.1}$$

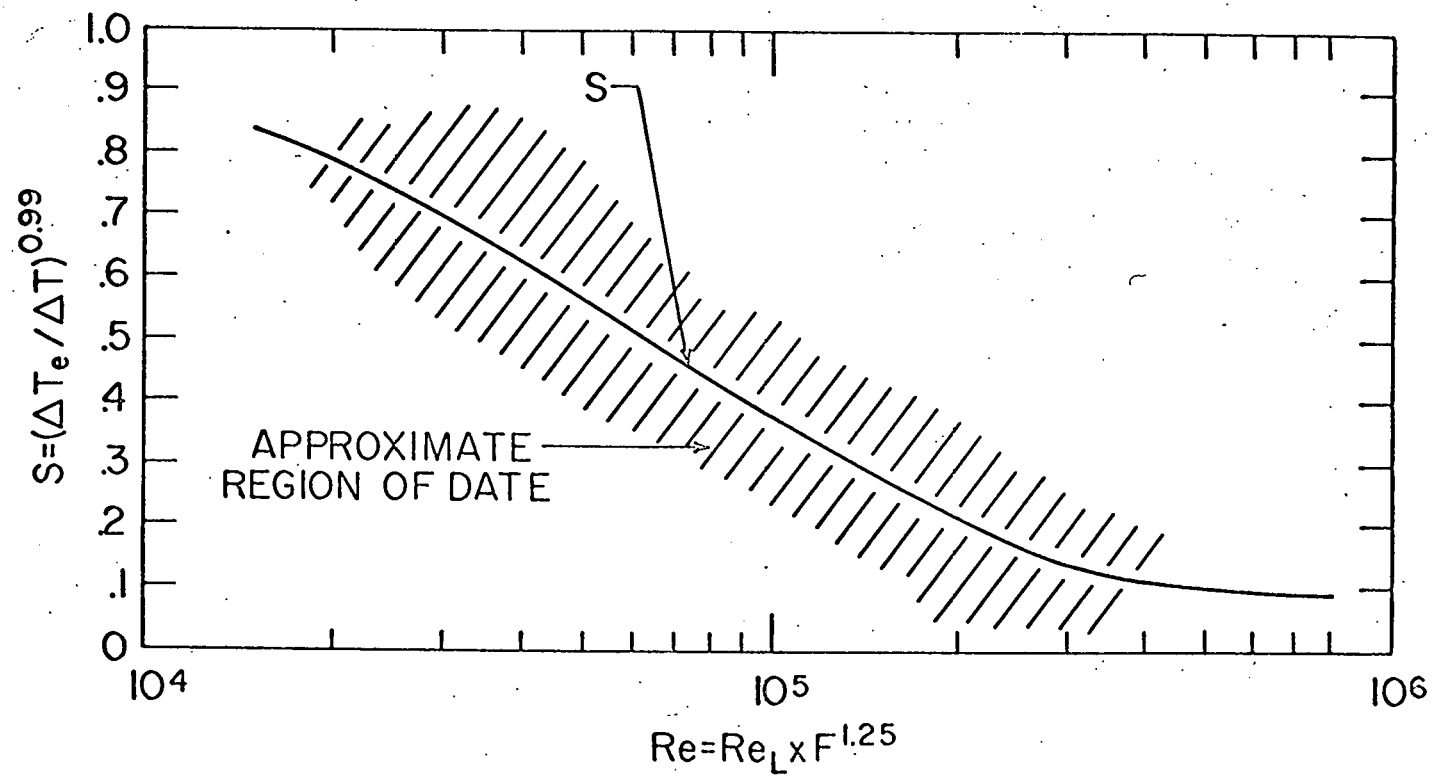
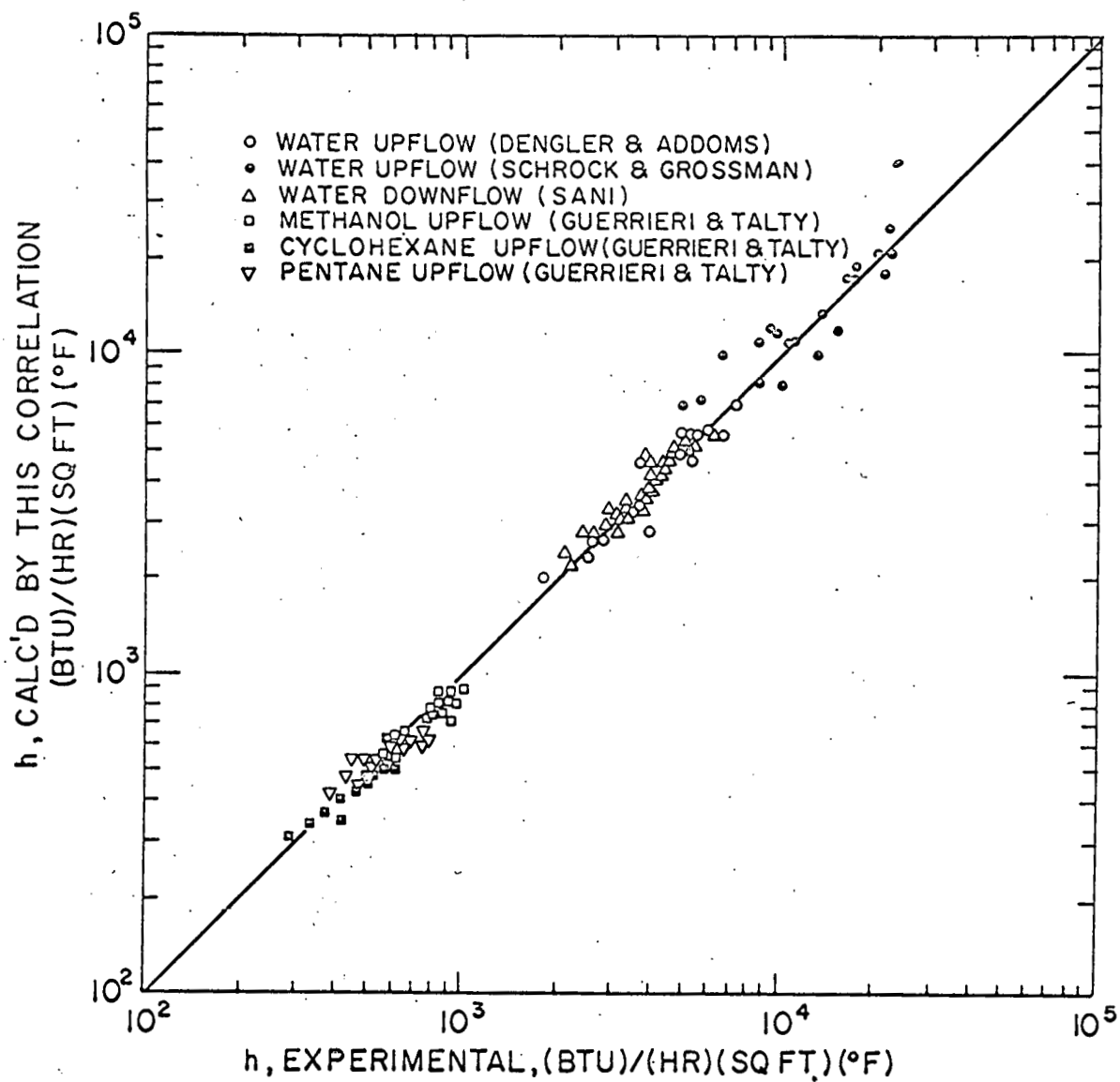
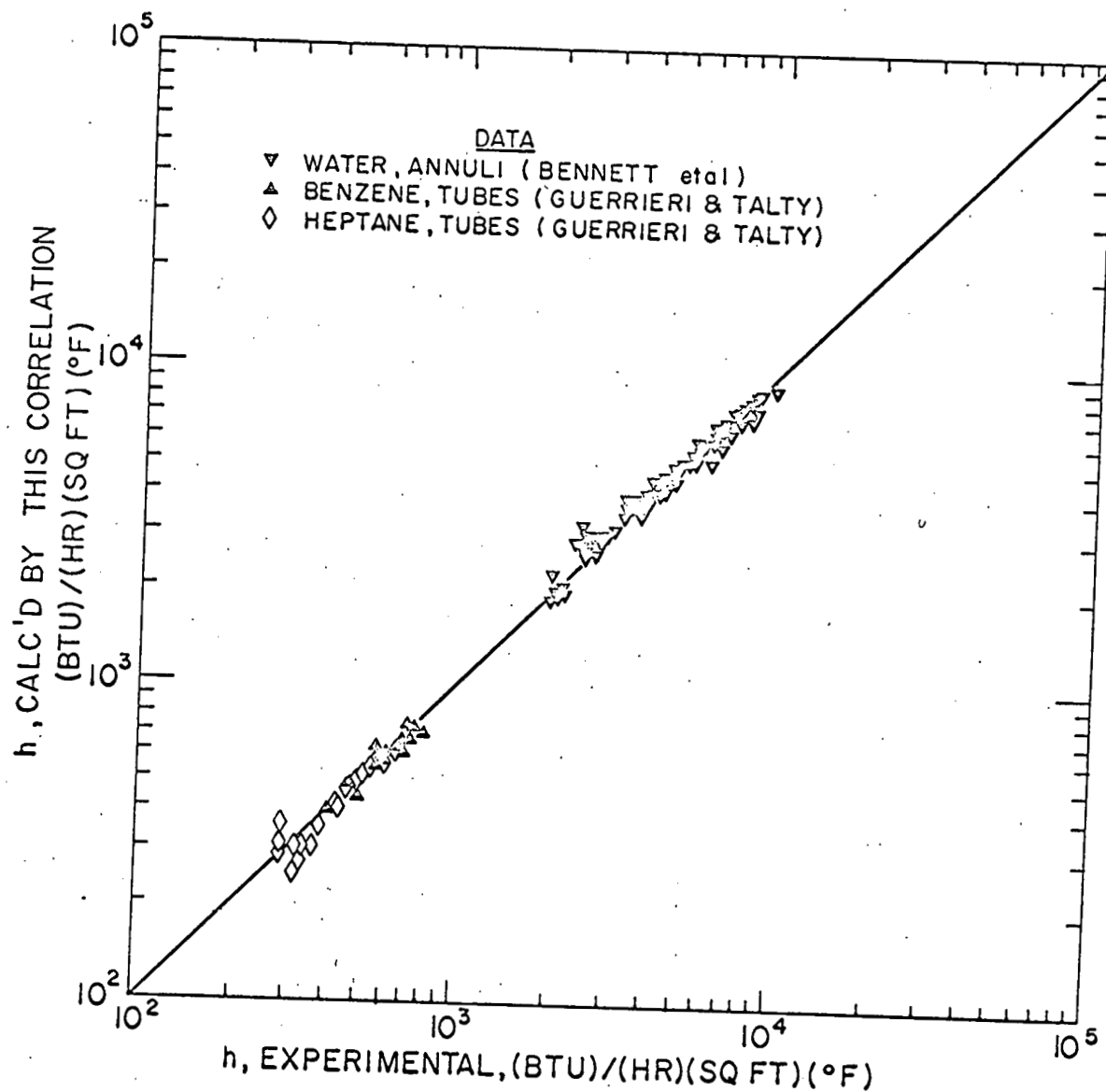


Fig. 8
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