No. 2673

Chart Correlation for Saturated Boiling Heat Transfer: Equations and Further Study

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INTRODUCTION

In 1976, the author[1] presented in graphical form a general correlation named CHART for the estimation of heat transfer coefficients during saturated boiling at subcritical heat flux in tubes and annuli. It was compared to 780 data points from 19 independent experimental studies and found to have a mean deviation of 14% using data that included eight fluids and a wide range of parameters. The correlation was shown to be applicable to both horizontal and vertical tubes and the difference between the two orientations was clearly quantified.

Because of its applicability to a wide range of fluids and conditions, including horizontal and vertical orientations, this correlation has drawn considerable attention from the scientific and engineering community. However, the use of the CHART correlation in computer calculations has been difficult because of its graphical form. After receiving several inquiries about availability of equations expressing this correlation, the author has developed and will present in this paper equations that represent the CHART correlation accurately.

Since its publication in 1976, this correlation has been tested against a large amount of additional data for tubes by the author and other researchers, with the results summarized here. Furthermore, in Ref 1 the correlation was compared with only a few data points for evaporation in annuli and there were questions regarding application to small annular gaps. A large amount of additional data for annuli have now been analyzed, and the results of this analysis are presented in this paper.

Because parametric trends predicted by the Shah correlation are not fully discussed in Ref 1, more detailed discussion will be undertaken here. Application to post-dryout region and calculation of the mean heat transfer coefficient are also discussed.

DESCRIPTION OF CHART CORRELATION

In order to make this paper comprehensible by itself, the correlation presented in Ref 1 is briefly recapitulated. Fig. 1 shows the correlation in graphical form. It uses four dimensionless parameters given by the following equations:

$$\psi = h_{TP}/h_{\ell} \qquad (1)$$

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ASHRAE Tr. 88(1), 1982, pp. 185-196

$$Co = \left(\frac{1}{x} - 1\right)^{0.8} (\rho_g/\rho_\ell)^{0.5} \quad (1)$$

$$Bo = q/(G\ i_{fg}) \quad (3)$$

$$Fr_L = \frac{G^2}{\rho_\ell^2\ gD} \quad (4)$$

The superficial heat transfer coefficient of liquid phase h_ℓ is calculated by the Dittus-Boelter equation as:

$$h_\ell = 0.023 \left[\frac{G\ (1-x)\ D}{\mu_\ell}\right]^{0.8} Pr_\ell^{0.4} \frac{k_\ell}{D} \quad (5)$$

In Fig. 1, four regimes of boiling are given. At Co > 1 is the nucleate boiling regime in which ψ is independent of Co and depends only on Bo. In this regime, the two-phase convective effects are negligible and heat transfer enhancement is determined solely by intensity of bubble nucleation. The line AB represents pure convective boiling (bubble nucleation completely suppressed) with the tube surface fully wet. The surface is fully wet for vertical tubes at any value of Fr_L, while for horizontal tubes, the surface is fully wet only if $Fr_L \geq 0.04$. For horizontal tubes with $Fr_L < 0.04$, part of the tube surface is dry and the heat transfer coefficient is lower than in vertical tubes. In between the convective boiling line AB and the nucleate boiling regime is the bubble suppression regime in which both bubble nucleation and convective effects are significant. With decreasing values of Co, i.e., increasing vapor quality, bubble nucleation is more and more suppressed until it completely disappears at line AB.

In Ref 1, the regime for $Bo < 0.5 \times 10^{-4}$ was left undefined because of lack of reliable experimental data. This region has now been filled out using the results obtained in Ref 2.

EQUATIONS FOR THE CHART CORRELATION

For N > 1.0

$$\psi_{nb} = 230\ Bo^{0.5} \quad , Bo > 0.3 \times 10^{-4} \quad (6)$$

$$\psi_{nb} = 1 + 46\ Bo^{0.5} \quad , Bo < 0.3 \times 10^{-4} \quad (7)$$

$$\psi_{cb} = 1.8/N^{0.8} \quad (8)$$

ψ is the larger of ψ_{nb} and ψ_{cb}. Thus if $\psi_{nb} > \psi_{cb}$, $\psi = \psi_{nb}$. If $\psi_{cb} > \psi_{nb}$, $\psi = \psi_{cb}$.

For $0.1 < N \leqq 1.0$

$$\psi_{bs} = F\ Bo^{0.5} \exp\ (2.74\ N^{-0.1}) \quad (9)$$

ψ_{cb} is calculated with Eq 8. ψ equals the larger of ψ_{bs} and ψ_{cb}.

For $N \leqq 0.1$

$$\psi_{bs} = F\ Bo^{0.5} \exp\ (2.47\ N^{-0.15}) \quad (10)$$

ψ_{cb} is calculated with Eq 8 and ψ equals the larger of ψ_{cb} and ψ_{bs}. The constant F in Eqs 9 and 10 is as follows:

$$Bo \geqq 11 \times 10^{-4}, \qquad F = 14.7 \quad (11)$$

$$Bo < 11 \times 10^{-4}, \qquad F = 15.43 \tag{12}$$

The dimensionless parameter N is defined as follows:

For vertical tubes at all values of Fr_L and for horizontal tubes with $Fr_L \geqq 0.04$,

$$N = Co \tag{13}$$

For horizontal tubes with $Fr_L \leqq 0.04$,

$$N = 0.38\ Fr_L^{-0.3}\ Co \tag{14}$$

The foregoing equations can be easily programmed for a computer or a hand-held calculater. These agree with curves within $\pm$ 6% over most of the CHART, with two exceptions. Firstly, at Co = 0.004 and $\bar{B}o = 50 \times 10^{-4}$, equations over-predict by about 11%, but this is of little consequence because there were no data in this region and it generally falls in the post-dryout portion of evaporator. Secondly, for horizontal tubes at $Fr_L < 0.04$ and $Bo < 1 \times 10^{-4}$, the equations can in some cases underpredict by as much as 20% for Co between 0.3 and 1.0. Equations that faithfully reproduce the curves in this range would be complicated, and because low Bo are not commonly used, development of such equations was not considered worthwhile. For horizontal tubes at $Fr_L < 0.04$, these equations are recommended only for $Bo \geq 1 \times 10^{-4}$. For horizontal tubes with $Fr_L \geq 0.04$, and for vertical tubes at any Fr_L, these equations are recommended for all values of Bo without restriction.

COMPARISON WITH ADDITIONAL TUBE DATA

The correlation in its graphical form has been compared with a large amount of data for boiling in tubes besides those given in Ref 1 and results of these comparisons are discussed below.

Collier[3] compared the correlation with the data of Bandel and Schlünder[4] for evaporation of R-11, R-12, and R-22 in electrically heated horizontal tubes and found good agreement. Chaddock and Buzzard[6] have compared the correlation with the data of Mathur[5] for R-22 as well as their own R-502 data, finding good agreement. The study with R-502 is specially interesting because values of Fr_L were varied from 0.008 to 0.5. The effect of this parameter was found to be in substantial agreement with the correlation.

Dembi et al[7] analyzed 804 data points from the tests of Lavin,[8] Chawla,[9] Rhee,[10] and Bandel.[11] The data were for R-11, R-12 and R-22 in tubes of diameter 6 to 25 mm. They tried a number of correlations but only those of Shah,[1] Chawla,[9] Bandel,[11] and Chen,[12] were found to give reasonable agreement. The Shah correlation was found to have a mean deviation of 23% while the Chen correlation had a mean deviation of 47%. The Shah correlation was found to generally under-predict the data while the Chen correlation generally overpredicted. While a mean deviation of 23% does not indicate excellent correlation, it is acceptable for a general correlation. The Dembi et al analysis also shows that use of the Chen correlation for horizontal tubes should be avoided.

The author compared the CHART with the data of Uchida and Yamaguchi[13] for R-12 evaporating in an electrically heated 6.4 mm ID horizontal tube and found good agreement.. The author also analyzed the data of Rounthwaite and Clouston[14] for boiling of water in a horizontal tube 40.6 mm ID with a hairpin bend at pressure between 14 and 42 bars. Most of the data points for subcritical heat fluxes were within 30% of the CHART with the maximum deviation about 40%.

BOILING IN ANNULI

In the Appendix to Ref 1, the recommendation was made that for boiling in annuli, h_ℓ be calculated by Eq 5 with D replaced by an equivalent diameter D_{EQ} according to the size of annular gap δ as given in the following:

$$\delta > 4\text{mm},\ D_{EQ} \equiv D_{HYD} = \frac{4 \times \text{flow area}}{\text{wetted perimeter}} \quad (15)$$

$$\delta < 4\text{mm},\ D_{EQ} = D_{HP} = \frac{4 \times \text{flow area}}{\text{heated perimeter}} \quad (16)$$

It is interesting to note that Chen[12] recommends use of D_{HP} for all annular gaps, although the only data analyzed by him were those of Bennet et al[15] with annular gaps of 3.08 and 2.23 mm. The present author's recommendations were based on several data sets for saturated and subcooled boiling and more data have now been analyzed as reported here.

In carrying out further data analysis, another method of calculating the single phase heat transfer coefficient was also considered. Many researchers have represented their single-phase heat transfer measurements by the following equation:

$$h_L = 0.023E \left(\frac{G\ D_{HYD}}{\mu_\ell}\right)^{0.8} Pr_\ell^{0.4} \frac{k_\ell}{D_{HYD}} \quad (17)$$

The parameter E is a function of geometrical factors, most commonly (D_o/D_i). A variety of expressions for E have been proposed by various researchers.[1]

Alferov and Rybin[16] compared the values of E proposed by five researchers and found that they differed widely. Upon carrying out a detailed experimental study for heating on the outer tube or both tubes, they found that E = 1. However, for heating on the inner tube alone, they found:

$$E = (D_o/D_i - 1)^{0.12} \quad (18)$$

These experiments were conducted with D_i = 15 mm and D_o/D_i from 1.13 to 1.66. The superficial liquid phase heat transfer coefficient is then calculated by,

$$h_\ell = h_L\ (1-x)^{0.8} \quad (19)$$

Data analysis was performed in the following two ways:

1. According to the recommendation in Ref 1, i.e., calculating h_ℓ with Eq 5 using D_{EQ} from Eq 15 or 16.

2. Calculating h_ℓ using the Alferov-Rybin correlation with E = 1 for external or bilateral heating. For internal heating, E calculated by Eq 18.

The results of this data analysis are summarized in Tab. 1. The mean deviation for the 736 data points analyzed is 17.3% according to the first method and 17.1% according to the second method. Thus the use of the Alferov-Rybin correlation for calculating single-phase heat transfer does not significantly improve the accuracy. Furthermore, the wide discrepancy in the single-phase correlations of various researchers suggests that the Alferov-Rybin correlation may not be generally applicable. Hence, the author's recommendation is to use the method outlined in Ref 1.

The data listed in Tab. 1 cover a very wide range of pressure, flow rate, heat flux, and qualities. Furthermore, these include both internal and bilateral heating. While some data points show large scatter, this does not seem to be related to either the annular gap or the pressure. Thus, while the data of Tarasova and Orlov[17] at high pressure with δ = 3.3 mm show a mean deviation of 45%, their data with δ = 1.06 mm at the same pressure have a mean deviation of 20%. It cannot be inferred that the correlation fails at high pressure or with small annular gaps, since some scatter is found under all conditions.

The data of Adorni et al[18] were generally 10 to 20% higher than the correlation, because the primary purpose of these tests was to measure critical heat flux, hence all measurements were done near the exit. Measurements near the exit are generally high, partly because of conduction losses through supports and electrical heating lugs and partly because of disturbance of flow caused by exit effects. (For discussion on this topic, see Refs 19 and 24). Hence the fact that the Adorni et al [18] data are generally 10 to 20% higher than the correlation is understandable. Furthermore, the data at the lowest mass flux (about 1000 kg/m^2s) are badly scattered, suggesting unstable operation. Data other than those at 1000 kg/m^2s are plotted in Fig. 2, which shows good agreement between measurements and this correlation.

PARAMETRIC TRENDS

The all liquid heat transfer coefficient is essentially constant as the liquid properties very little along the length of evaporator. Hence a plot of h_{TP}/h_L represents the variation of the two-phase heat transfer coefficient. In Figs. 3 to 6, h_{TP}/h_L is plotted against vapor quality at three boiling number values and ρ_g/ρ_ℓ from 0.001 to 0.9. The plots are for vertical tubes and also apply to horizontal tubes if $Fr_L \geq 0.04$. At $Fr_L < 0.04$, h_{TP}/h_L is lower but the parametric trends are the same. It should be noted that the curves in these figures are generally valid only if the heat flux is below the critical value and the vapor quality is below the dryout quality.

APPLICATION TO POST DRYOUT CONDITIONS

This correlation is intended for subcritical heat fluxes and should normally not be used for post critical heat flux region. The dryout quality should be determined by suitable predictive techniques, for example the Shah correlations,[21,22] and the CHART applied only for qualities less than the dryout qualities. For guidance on calculations in the post-dryout region, the text by Collier[26] is suggested as a starting point. The paper by Verma[27] provides useful information and references for refrigerant evaporators.

The calculations by the methods outlined above are difficult, but short cut is possible if the variation of heat transfer coefficients in the actual evaporator is known to be similar to that predicted by the CHART. As was stated in Ref 1, the variations of heat transfer coefficients found in actual refrigerant evaporators are similar to those shown in Figs. 3 and 4. This becomes understandable when it is noted that the density ratio in refrigerant evaporators is usually between 0.001 and 0.02. It should also be noted that well-verified correlations for post-dryout heat transfer of refrigerants are not available. In view of all these factors, the author feels that his recommendation, that the CHART may be used for refrigerant evaporators in the post-dryout region (Ref 1), is justified. This recommendation is only for those evaporators with negligible oil content. Presence of significant amounts of oil in R-11, R-12, and R-22 causes dryout to accur at low vapor qualities and the variations of heat transfer coefficients generally differ greatly from those with oil-free refrigerants.

CALCULATION OF MEAN HEAT TRANSFER COEFFICIENT

In Ref 1, the author calculated mean heat transfer coefficients by using the arithmetic mean quality in the CHART correlation. Although several authors, for example Anderson et al[23] and Chaddock and Noerager,[24] used the same method with other correlations, study of Figs. 3 to 6 shows that such a procedure could often be inaccurate. This method would give reliable results only if the heat flux is constant, variation of vapor quality with length is linear, and the change in quality is comparatively small. The correct method is to calculate the local heat transfer coefficients and then obtain the mean heat transfer coefficient by the following equation:

$$\overline{h}_{TP} = \frac{\overline{q}}{\frac{1}{L}\int_o^L (T_w - T_b)\, dL} \qquad (20)$$

The calculations using mean quality should be done only for rough estimates. Now that the CHART has been converted to equations, accurate computer calculations can be done and there is little justification for using crude approximations.

SUMMARY AND CONCLUSIONS

1. Equations representing the author's graphical correlation CHART have been presented which can be easily programmed for computer calculations.

2. Results of comparison of the correlation by the author and other researchers with data for boiling in tubes have been presented. Most of these show good agreement with the correlation.

3. The large amount of data for boiling in annuli analyzed show that the recommendation in Ref 1 to use D_{HYD} for annular gaps wider than 4 mm and D_{HP} for gaps narrower than 4 mm, gives satisfactory correlation. Applicability of the correlation to bilateral heating has also been confirmed.

4. The parametric effects of density ratio, quality and boiling number according to the CHART have been shown in several figures to provide better insight into the correlation and the phenomena involved.

5. The calculation of mean heat transfer coefficients and the application to the post-dryout region have been discussed and recommendations made.

6. The correlation has now been verified with some 3000 data points for 12 fluids up to a reduced pressure of 0.89, in tubes up to 41 mm dia. and in annuli with gaps from 1.1 to 6.2 mm. Thus, one can feel considerable confidence in its reliability and general applicability.

NOMENCLATURE

Bo	boiling number, defined by Eq 3
Co	Convection number, defined by Eq 2
D	internal diameter of tube
D_{EQ}	equivalent diameter of annulus
D_i	diameter of inner tube of an annulus
D_o	diameter of outer tube of annulus
D_{HYD}	hydraulic equivalent diameter = $(D_o - D_i)$
D_{HP}	equivalent diameter based on heated perimeter, defined by Eq 16
E	geometrical factor for annulus, obtained from Eq 19
F	constant given by Eqs 11 and 12
Fr_L	Froude number assuming all mass to be flowing as liquid, given by Eq 4
G	mass flow per unit area per unit time
g	accelaration due to gravity
h_L	heat transfer coefficient assuming all mass to be flowing as liquid
h_{TP}	local two-phase heat transfer coefficient
$\bar{h}_{TP}$	mean heat transfer coefficient
i_{fg}	latent heat of vaporization
k_ℓ	thermal conductivity of liquid

L length of evaporator

N parameter defined by Eqs 13 and 14

$\bar{q}$ mean heat flux

T_w wall temperature

T_b bulk temperature of boiling fluid

x thermodynamic vapor quality

Greek Symbols

ρ_ℓ density of liquid

ρ_g density of vapor

μ_ℓ dynamic viscosity of liquid

ψ $= h_{TP}/h_\ell$

ψ_{bs} value of ψ in the bubble supression regime

ψ_{cb} value of ψ in the pure convective boiling regime

ψ_{nb} value of ψ in the pure nucleate boiling regime

δ annular gap $= (D_o - D_i)/2$

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Table 1: Summary of comparison of saturated boiling data with the Shah correlation in graphical form[1]. All data are for water in vertical annuli.

SOURCE	D_i mm	δ mm	Heated Tube	p_r	G kg/m^2s	$q \times 10^{-6}$	x%	$Re_L \times 10^{-3}$	$Bo \times 10^4$	Co	Mean Dev.% a	Mean Dev.% b	No. of Data Points
Tarasova & Orlov[17]	12.97	1.06	Inner	0.58 0.89	2635 5700	0.494 1.116	1 10	71 153	1.6 3.6	7.6 18.9	19.8	19.0	9
	8.5	3.3	Inner	0.58 0.89	1360 2720	0.550 1.215	0 13	59 163	2.2 9.6	1.6 37.0	45.3	22.5	10
Morozov[20]	14.24	2.88	Inner	0.23 0.38	6085 11071	0.261 0.375	0	190 345	0.3	very large	12.2	4.1	6
Adorni et al[18]	5.02	1.61	Inner both*	0.31	980 1010	0.098 0.870	15 70	34 35	0.7 5.9	0.11 0.91	42.9	40.41	23
	5.02	1.61	Inner both*	0.31	1490 3800	0.090 0.812	7 70	51 128	0.3 3.6	0.11 1.7	14.6	14.6	64
Collier et al[19]	15.8	3.08	Inner	0.005 0.011	105 285	0.100 0.794	0 62	6 16	0.6 9.8	0.02 1.3	19.2	20.7	164
	9.5	6.23	Inner	0.005 0.010	135 273	0.197 0.396	0 66	7 15	3.3 13.2	0.01 4.4	16.0	16.0	112
Bennet et al[15]	9.5	2.23	Inner	0.006 0.011	152 294	0.200 0.399	13 59	3 6	3.1 11.9	0.02 0.13	16.0	12.5	64
	15.8	3.08	Inner	0.005 0.011	70 279	0.100 0.499	0 55		1.9 13.6	0.02 2.6	14.8	14.9	288
All	5.02 15.8	1.06 6.23	Inner Both	0.005 0.89	70 11071	0.100 1.215	0 70	1.4 345.0	0.3 13.6	0.02 18.9	17.3	17.1	736

* Simultaneous boiling on both tubes

a h_l calculated according to Ref. 1, i.e. using D_{EQ} from Eq 15 and 16

b h_l calculated by Alferov-Rybin correlation, Eq 17, 18, and 19

$$\text{Deviation} = \frac{(\text{Prediction-Measurement})}{\text{Measurement}}, \quad \text{Mean Deviation} = \frac{\Sigma\,[\text{Absolute Value of Deviation}]}{\text{no. of data ponts}}$$

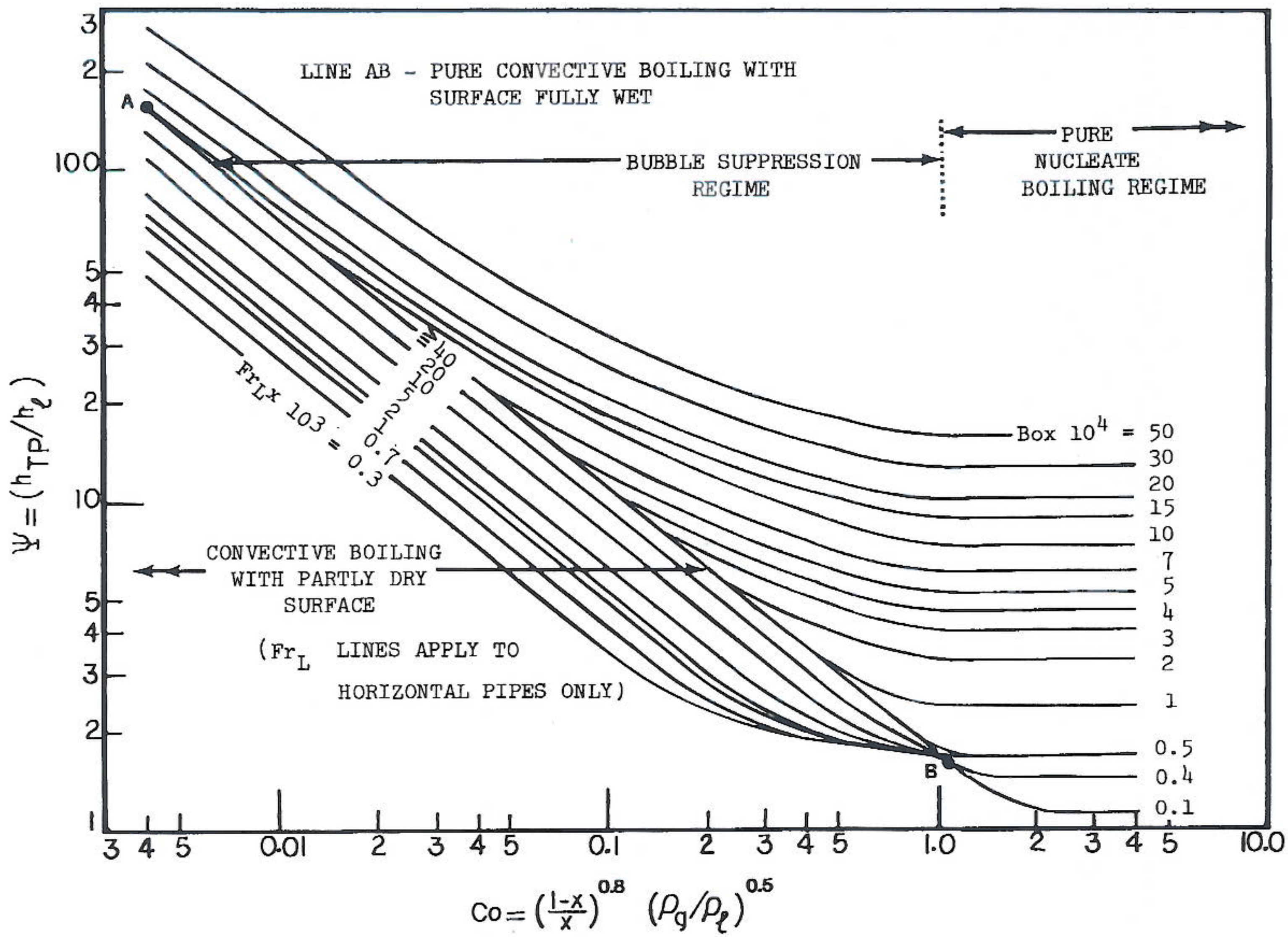

Figure 1. The Chart correlation of Shah[1]

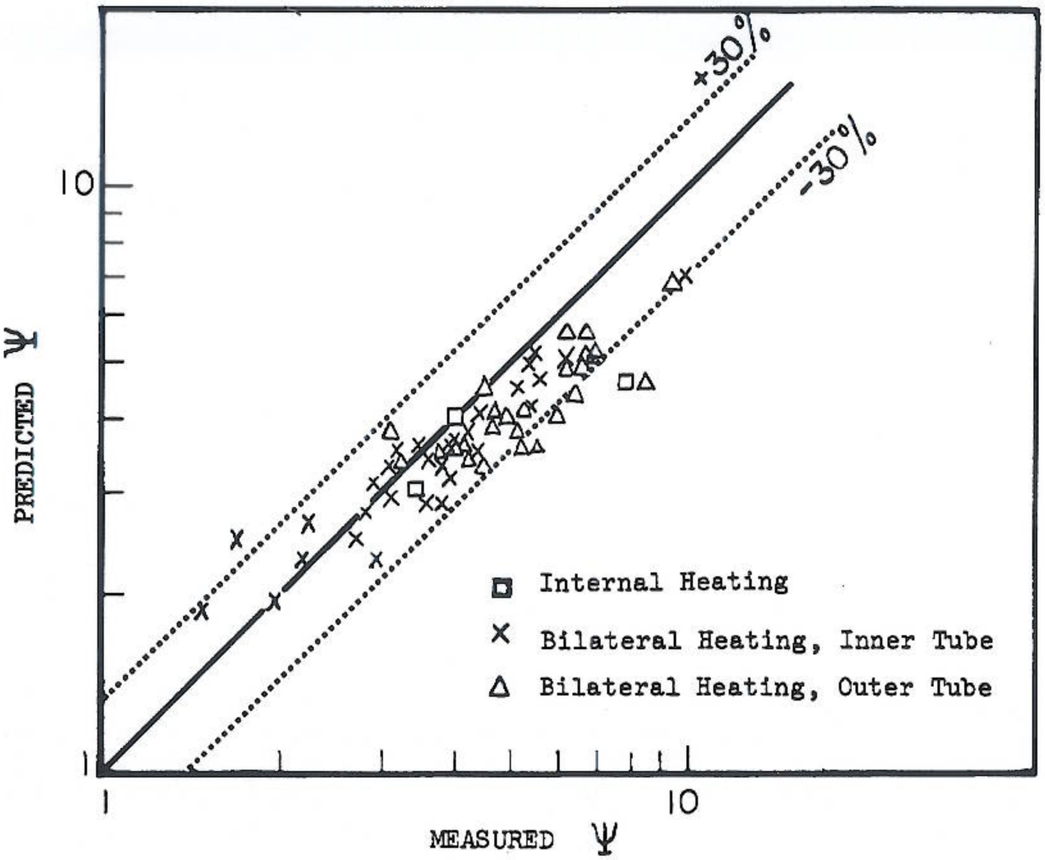

Figure 2. Comparison of the Shah correlation with data of Adorni et al[18]

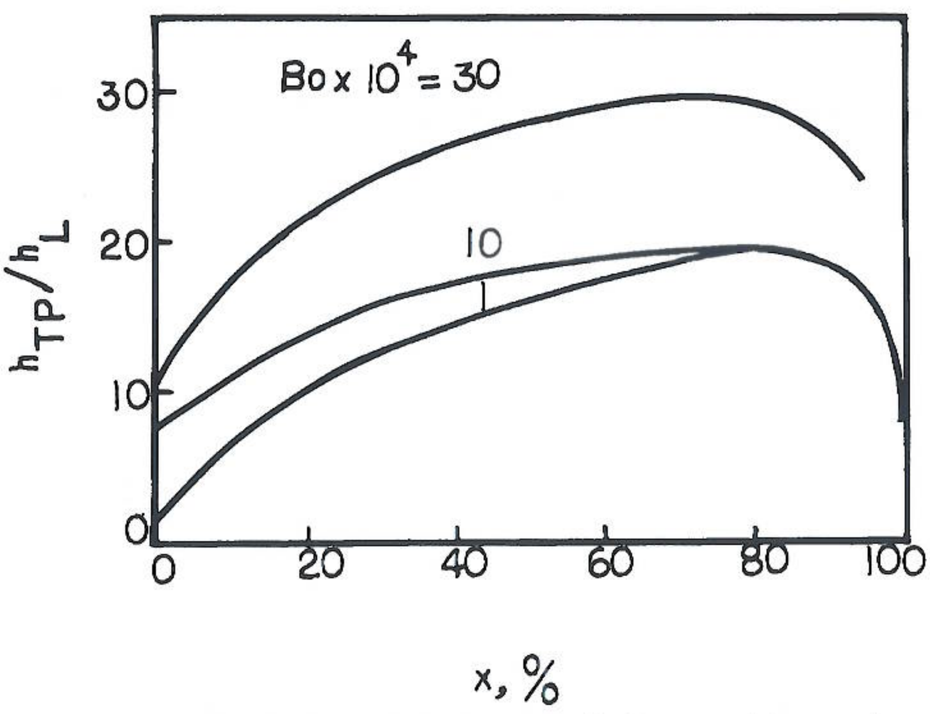

Figure 3. Predictions of the Shah correlation at ρg/ρl = 0.001

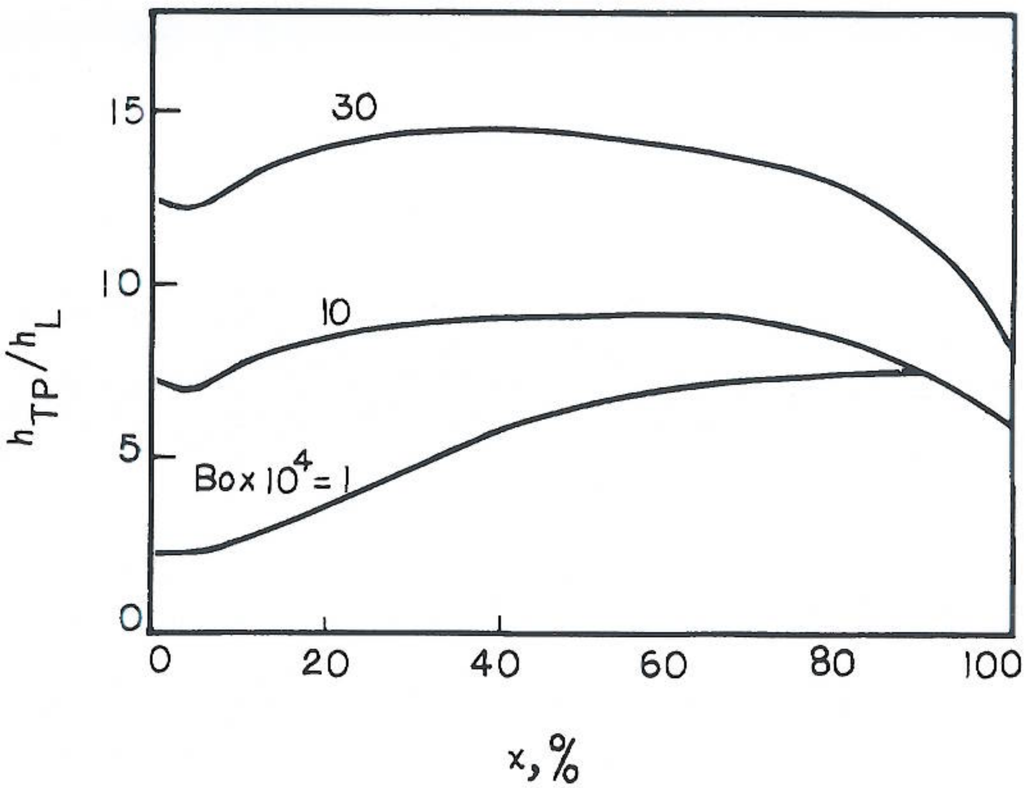

Figure 4. Predictions of the Shah correlation at ρg/ρl = 0.01

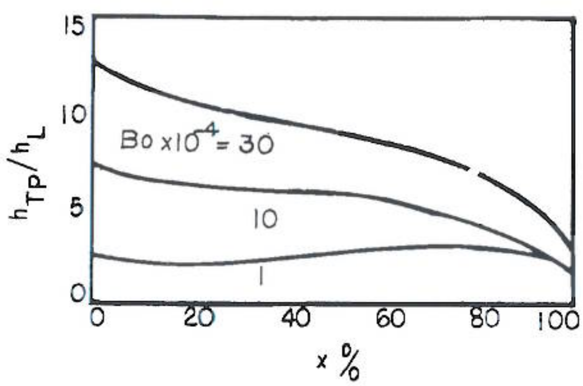

Figure 5. Predictions of the Shah correlation at ρg/ρl = 0.1

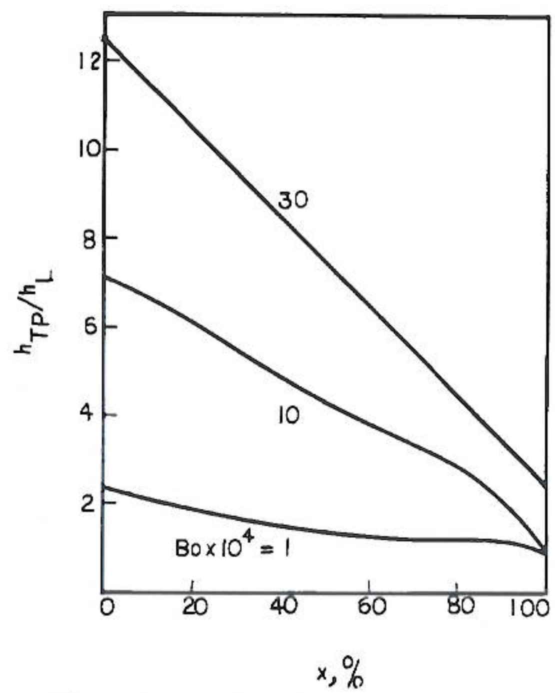

Figure 6. Predictions of the Shah correlation at ρg/ρl = 0.9