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COMPARATIVE STUDY OF FORCED  
CONVECTION BOILING HEAT TRANSFER  
CORRELATIONS FOR CRYOGENIC FLUIDS

by

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## ABSTRACT

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This study compares predictive reliability of several common forced convection boiling heat transfer correlations using available cryogenic experimental data. A statistical method is used to compare the correlations and results indicate that none of the proposed predictive methods fall in a very respectable range of reliability and, furthermore, for design purposes, the simpler correlations seem to compare favorably with the more complex approaches.

COMPARATIVE STUDY OF FORCED  
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INTRODUCTION

The designer of cryogenic systems is frequently faced with the problem of determining the coefficients for forced convection boiling heat transfer. Unfortunately, because of the complexity of the heat transfer mechanism when boiling is involved, no generally accepted correlation for heat transfer coefficients has emerged. This is in spite of the efforts of many people who have attempted to derive, either empirically or theoretically, such a correlation. Consequently there are many predictive expressions to be found in the literature and this paper has, as an attempt to aid the designer, undertaken to test and compare the more familiar expressions using the available cryogenic data. A statistical approach was used to compare the correlations and the results are limited to only hydrogen in the nucleate and film boiling regions because of a lack of complete, tabulated experimental data for

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the other cryogenic fluids and because of insufficient data in the transition boiling regions. A more detailed treatment of this subject together with a pool boiling study and some properties data may be found in an NBS Tech Note No. 317 [1].

There are effects of variables not included or not fully tested by the correlations which should be considered in some design situations.

These variables are pressure effects particularly near the critical point, effects of appreciable subcooling, effects in low gravity fields and the influence of surface orientation, chemistry and roughness, particularly for the wetted wall condition. Section 4 of the NBS Tech Note 317 previously mentioned in the Introduction provides the interested reader with an introduction to these boiling variables along with literature references pertaining to the subject.

#### BOILING REGIMES AND DATA

Some general divisions for the forced convection boiling regions have been proposed, for example, by Davis [2]:

- (1) Region I - the nucleate boiling (wet wall) region where the nucleate boiling contribution is significant, as for low velocity flows.
- (2) Region II - the wet wall region where the forced convection effects are more significantly controlling for high velocity flows.
- (3) Region III - The dry wall or liquid deficient region where

the heat transfer is through a vapor film to a liquid or two-phase core (film boiling).

The transition from the wet wall condition to the dry wall condition is often of prime design interest since the heat transfer process for the dry wall condition is less effective than for the wet wall condition. The transition occurs when the liquid film is depleted either by vaporization at the wall or by entrainment and/or evaporation at the liquid film-vapor core interface [3]. Table I summarizes the experimental data used in this study which, as mentioned in the Introduction, were hydrogen data only.

#### PREDICTIVE EXPRESSIONS

The predictive expressions fall generally into two categories:

- (1) Correlation of a simple or modified Nusselt number ratio with the Martinelli correlating parameter ( $\chi_{tt}$ ) or a similar term, primarily reflecting quality. The Nusselt number ratio used is the ratio of the experimental (or actual) Nusselt number to that value obtained by use of a Dittus-Boelter or Sieder-Tate type of equation with either single-phase properties or some modifications involving two-phase properties.
- (2) Simple superposition, that is, addition of the separately determined pool boiling and forced convection (without

TABLE I  
DATA USED BY THIS STUDY

Authors and References	Test Medium	Test Section Geometry and Material	Boiling Region	Experimental Test Conditions								Type of Heating
				Inlet Press	$\Delta T$ $T_{wall} - T_{sat}$ of bulk boiling fluid	Mass Velocity		Heat Flux				
						(atm)	(psia)	(K)	(R)	$\frac{g}{sec-cm^2}$	$\frac{lb}{hr-ft^2}$	
Core, Harkee, Misra, and Sato [4]	Hydrogen	Vertical, stain- less steel, 0.168" I.D.,	Film	2	30	27.8	50	51.5	378,000	1.6	5200	Electrical
				to 9.4	to 138	to 694	to 1250	to 98.8	to 725,000	to 820	to $2.6 \times 10^6$	
Hendricks Graham, Hsu, and Friedman [5]	Hydrogen	Vertical, inconel, 0.313" I.D., 12.00" long	Film	1.8	27	27.8	50	57.9	425,000	37	118,600	Electrical
				to 4.9	to 72	to 389	to 700	to 166	to $1.22 \times 10^6$	to 165	to 524,000	
Wright and Walters [6]	Hydrogen	Horizontal, cop- per, 0.250" I.D., 6.00" long	Nucleate and Film	1.4	20	.56	1	41.9	306,000	.95	3,000	Electrical
				to 2.7	to 40	to 156	to 280	to 118	to 865,000	to 39	to 123,000	

boiling) contributions.

The correlations used and definitions of terms are given in Table II. Terms that are defined in one correlation are not repeated if the definition is the same.

### STATISTICAL TREATMENT OF DATA

A statistical approach was used to quantitatively compare all the correlations given in Table II. It is important to note that no conclusions regarding the absolute reliability of the correlations are implied by this study because the data used are limited in number of points, range of fluid properties, and by experimental systems. Furthermore, no attempt was made to analyze the data for accuracy. However, it is felt that these data permitted a comparative study.

Since there were significant differences in the three sets of data considered, as illustrated in Figures 1 through 7, all of the calculations were repeated for only one set of data, that of Hendricks, et al. [5], and compared to results of calculations that were made using all three sets of data.

Table III summarizes the results which were obtained as follows:

- (1) Using the method of least squares by means of a digital computer, an equation of the best fit curve for each of the plots shown in Figures 1 through 7 was determined.
- (2) From the resulting least squares fit curve equation or the superposition type of predictive equation, an  $h_{pred}$  was

TABLE II · CORRELATIONS USED

Film Boiling			DEFINITION OF TERMS		PLOT OF CORRELATION SHOWN IN
AUTHOR(S)	CORRELATION				
Hendricks, Graham, Hsu, and Friedman [5]	$\frac{Nu_{exp}}{Nu_{calc, f, tp}} = f(X_{ft})$ (1)	(1)	$Nu_{exp} = \frac{h_{exp} D}{K_v}$	$Re_{f, m, tp} = \frac{\rho_{f, m, tp} U_{avg} D}{\mu_{fv}}$	Figure 1  Figure 2
	or $\frac{Nu_{exp}}{Nu_{calc, f, tp}} = f(x)$ (2)	(2)	$Nu_{calc, f, tp} = 0.023 Re_{f, m, tp}^{0.8} Pr_{fv}^{0.4} \left( \frac{\mu_{fv}}{\mu_{fl}} \right)^{0.1}$ $X_{ft} = \left( \frac{1-x}{x} \right)^{0.9} \left( \frac{\rho_v}{\rho_l} \right)^{0.5} \left( \frac{\mu_l}{\mu_v} \right)^{0.1}$	$Pr_{fv} = \frac{Cp_{fv} \mu_{fv}}{K_{fv}}$ where $\rho_{f, m, tp} = \frac{1}{\frac{x}{\rho_l} + \frac{1-x}{\rho_v}}$ $U_{avg} = \frac{\dot{m}}{\rho_b A_c}$ $\rho_b = \frac{1}{\frac{x}{\rho_v} + \frac{1-x}{\rho_l}}$	
This Study	$\frac{Nu_{exp}}{Nu_{calc, v, sp}} = f(X_{ft})$ (3)	(3)	$Nu_{exp} = \frac{h_{exp} D}{K_v}$	$Re_{v, sp} = \frac{\rho_v U_{avg} D}{\mu_v}$	Figure 3  Figure 4
	or $\frac{Nu_{exp}}{Nu_{calc, v, sp}} = f(x)$ (4)	(4)	$Nu_{calc, v, sp} = 0.026 Re_{v, sp}^{0.8} Pr_v^{0.4} \left( \frac{\mu_v}{\mu_w} \right)^{0.14}$	where $Pr_v = \frac{Cp_v \mu_v}{K_v}$	
Ellerbrock, Livingood and Straight [7]	$\left( \frac{Nu_{exp}}{Nu_{calc, f, tp}} \right)^{0.4} (Bo No) = f(X_{ft})$ (5)	(5)	$Nu_{exp} = \frac{h_{exp} D}{K_{fv}}$		Figure 5  Figure 6
	or $\left( \frac{Nu_{exp}}{Nu_{calc, f, tp}} \right)^{0.4} (Bo No) = f(x)$ (6)	(6)	$Bo No = \frac{q}{\lambda G_{mix}}$		
von Glahn [8]	$\frac{Nu_{exp}}{Nu_{v, calc}} F_{tp} = f(X_{ft})$ (7)	(7)	$Nu_{exp} = \frac{h_{exp} D}{K_v}$ $Nu_{v, calc} = 0.023 Re_v^{0.8} Pr_v^{0.4}$ $F_{tp} = 20 \times 10^{-10} a(\beta)^{0.167} [18 - (X_{ft})^2]^{0.005} [1 - (X_{ft})^2]^{-0.687} (N_{bo no})$ $X_{ft} = \frac{x_f}{1-x_c}$	where $Re_v = \frac{\rho_b U_{avg} D}{\mu_v} = \frac{DG_{mix}}{\mu_v}$ , $\gamma = Re_v \left( 1 + \frac{2500}{\Gamma} \right)$ $a = \left[ 4.2 \left( 1 - \frac{Re_v^2 + 585 \times 10^4}{Re_v^2} \right) + 0.92 \right]$ ; $\Gamma = \frac{qD}{\mu_v \lambda}$ $\beta = \left[ \frac{g(\rho_l - \rho_v) D^2}{\sigma_l} \right]^{0.5}$ ; $N_{bo no} = \frac{\mu_v^2 \sqrt{g(\rho_l - \rho_v)}}{\rho_l (\sigma_l)^{0.5}}$ $a = \left\{ 0.5 \left[ 1 - \frac{(Le/D)^2}{(Le/D)^2 + 0.05} \right] + 0.13 \right\} = 0.13$ for $Le/D > 3.5$	Figure 7



TABLE II. CORRELATIONS USED (Continued)

Film Boiling			
AUTHOR(S)	CORRELATION	DEFINITION OF TERMS	PLOT OF CORRELATION SHOWN IN
This Study *	$h_{pred} = h_{conv, s.p.v.} + h_{film, pool, boil}$ (8)	$h_{conv, s.p.v.} = 0.026 Re_{\nu, s.p.v.}^{0.80} Pr_{\nu}^{0.33} \left( \frac{\mu_{\nu}}{\mu_f} \right)^{0.14} \frac{K_f}{D}$ [9] $h_{film, pool, boil} = \left\{ 4.94 \left[ \frac{(\Delta p_f)^{0.375}}{\sigma^{0.125}} \right] + 0.115 \left[ \frac{\sigma^{0.375}}{D(\Delta p_f)^{0.125}} \right] \left[ \frac{K_f^3 \lambda_f \rho_f}{\mu_f} \right]^{0.250} \Delta T^{-0.250} \right\}$ where $\lambda' = \left[ \frac{\lambda + 0.340 (C_p \rho_f \Delta T)^2}{\lambda} \right]$	Not Applicable
Nucleate Boiling			
This Study *	$h_{pred} = h_{conv, s.p.l.} + h_{nucleate, pool, boil}$ (9)	$h_{conv, s.p.l.} = 0.023 Re_l^{0.8} Pr_l^{0.4} \frac{K_l}{D}$ $h_{nucleate, pool, boil} = 0.487 (10)^{-10} \left[ \frac{K_l \rho_l^{1.282} Pr_l^{1.750} (C_p \rho_l)^{1.500}}{(\lambda \rho_v)^{1.500} \sigma^{0.506} \mu_l^{1.500}} \right] \Delta T^{1.500}$ [10] where $Re_l = \frac{DG_{mix}}{\mu_l}$ $Pr_l = \frac{(C_p \rho_l) \mu_l}{K_l}$	Not Applicable
Chen [11]	$h_{pred} = h_{fc} F + h_{f-2} S$ (10)	$h_{fc} = 0.023 Re_l^{0.8} Pr_l^{0.4} \frac{K_l}{D}$ $h_{f-2} = (1.22)(10)^{-3} \frac{K_l^{0.79} (C_p \rho_l)^{0.45} \rho_l^{0.49} (\Delta T)^{0.24} (\Delta p)^{0.75}}{\sigma_l^{0.5} \mu_l^{0.29} \lambda^{0.24} \rho_v^{0.24}}$ For values of $F$ and $S$ , see Sieder et al [12]	Not Applicable
Kutateladze [13]	$\frac{h_{pred}}{h_{conv, s.p.l.}} = \sqrt{1 + \left( \frac{h_{nucleate, pool, boil}}{h_{conv, s.p.l.}} \right)^2}$ (11)		Not Applicable

\* Basic idea of superposition is quite old. Variations are in the choice of expressions for the convective and pool boiling coefficients.

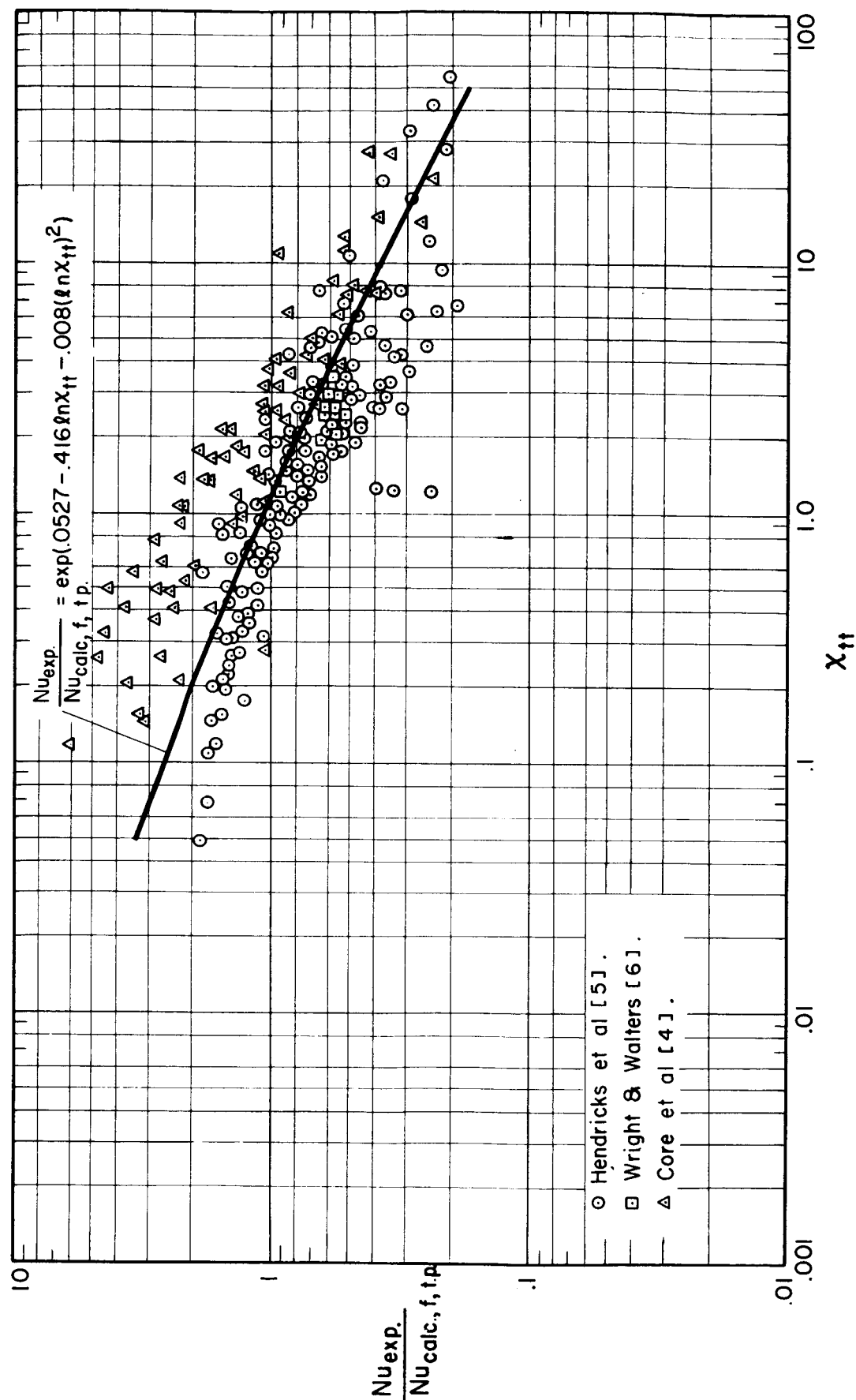


Figure 1. Two-phase Nusselt number ratio vs  $X_{tt}$

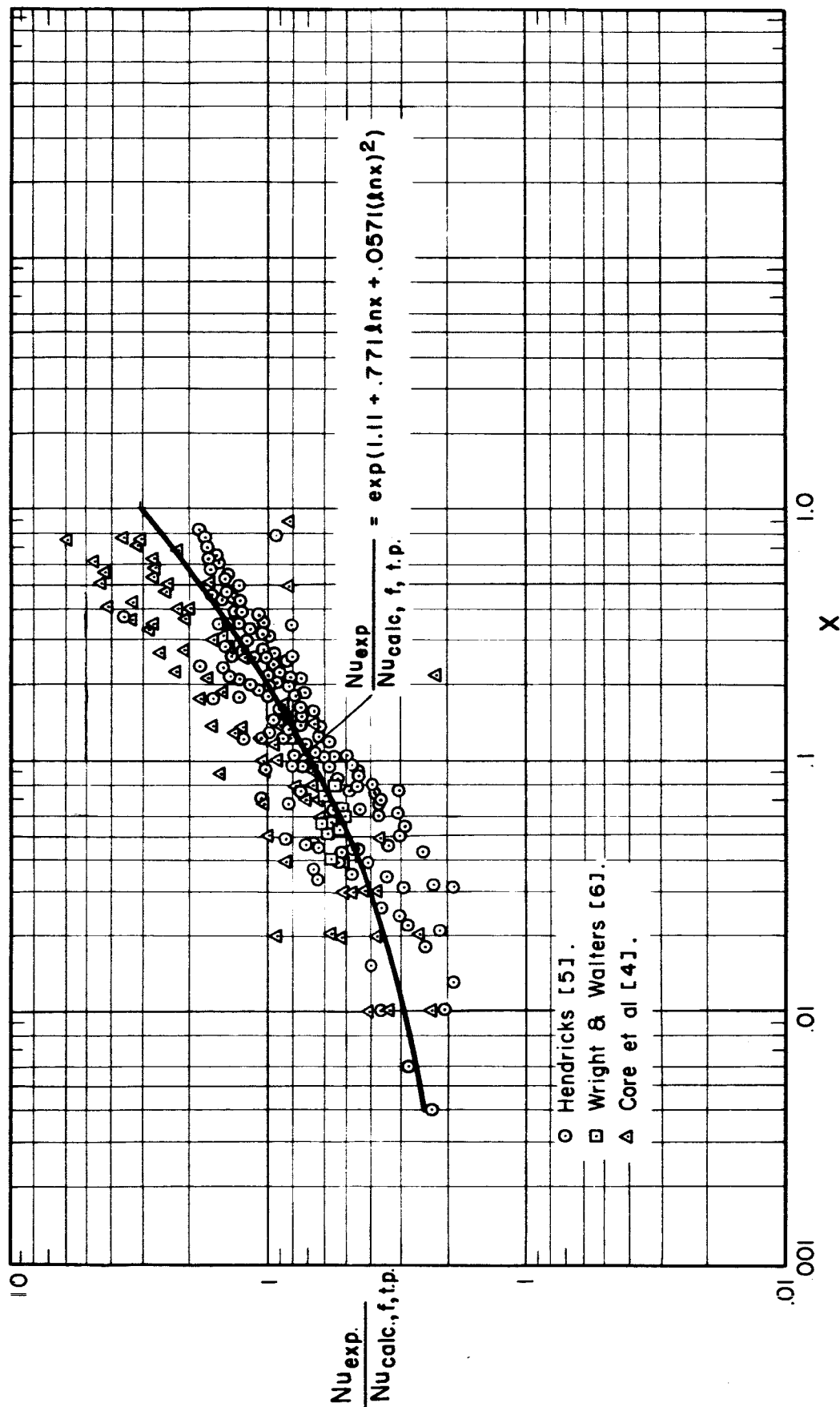


Figure 2. Two-phase Nusselt number ratio vs  $x$ (quality)

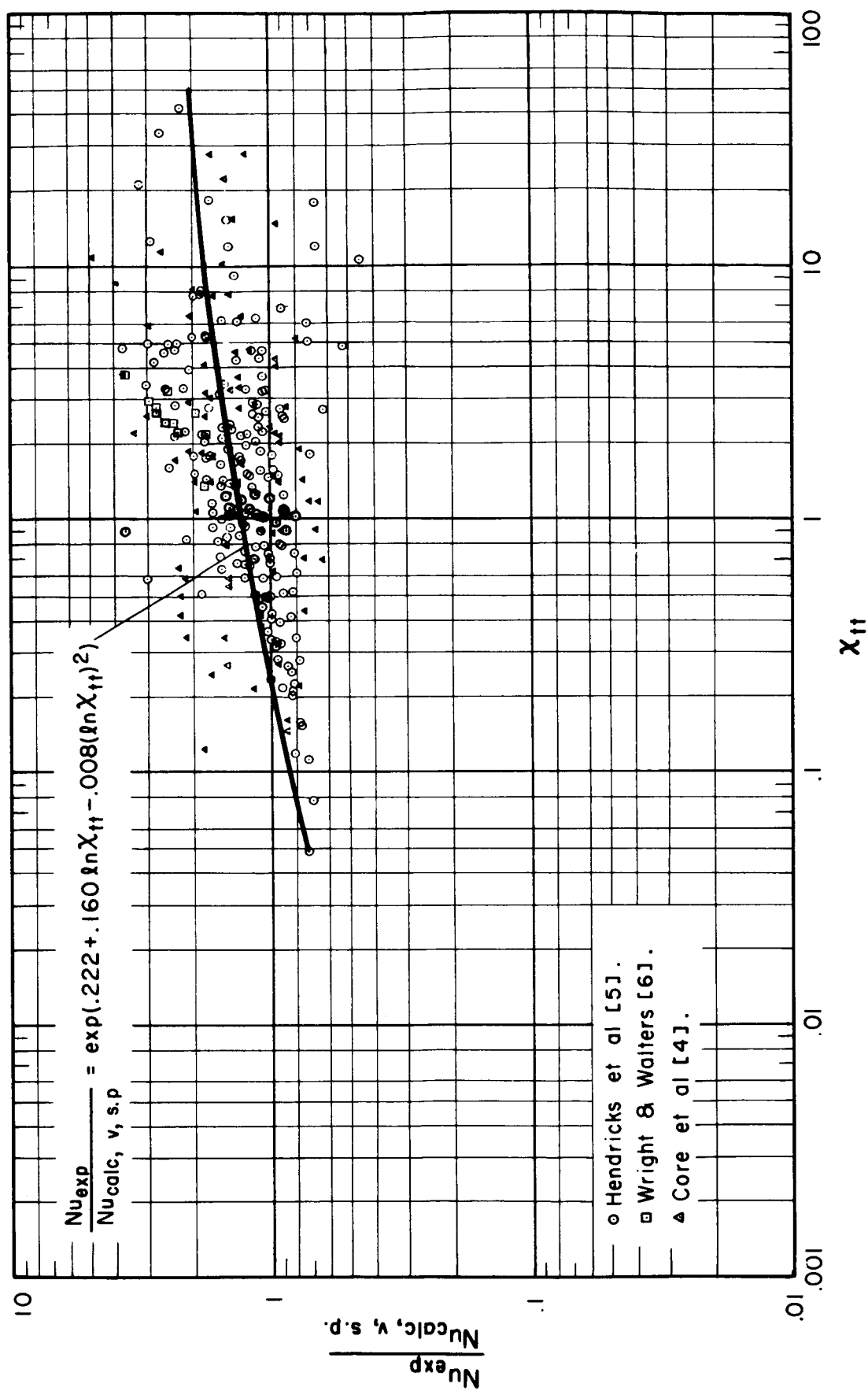


Figure 3. Single-phase Nusselt number ratio vs  $X_{tt}$

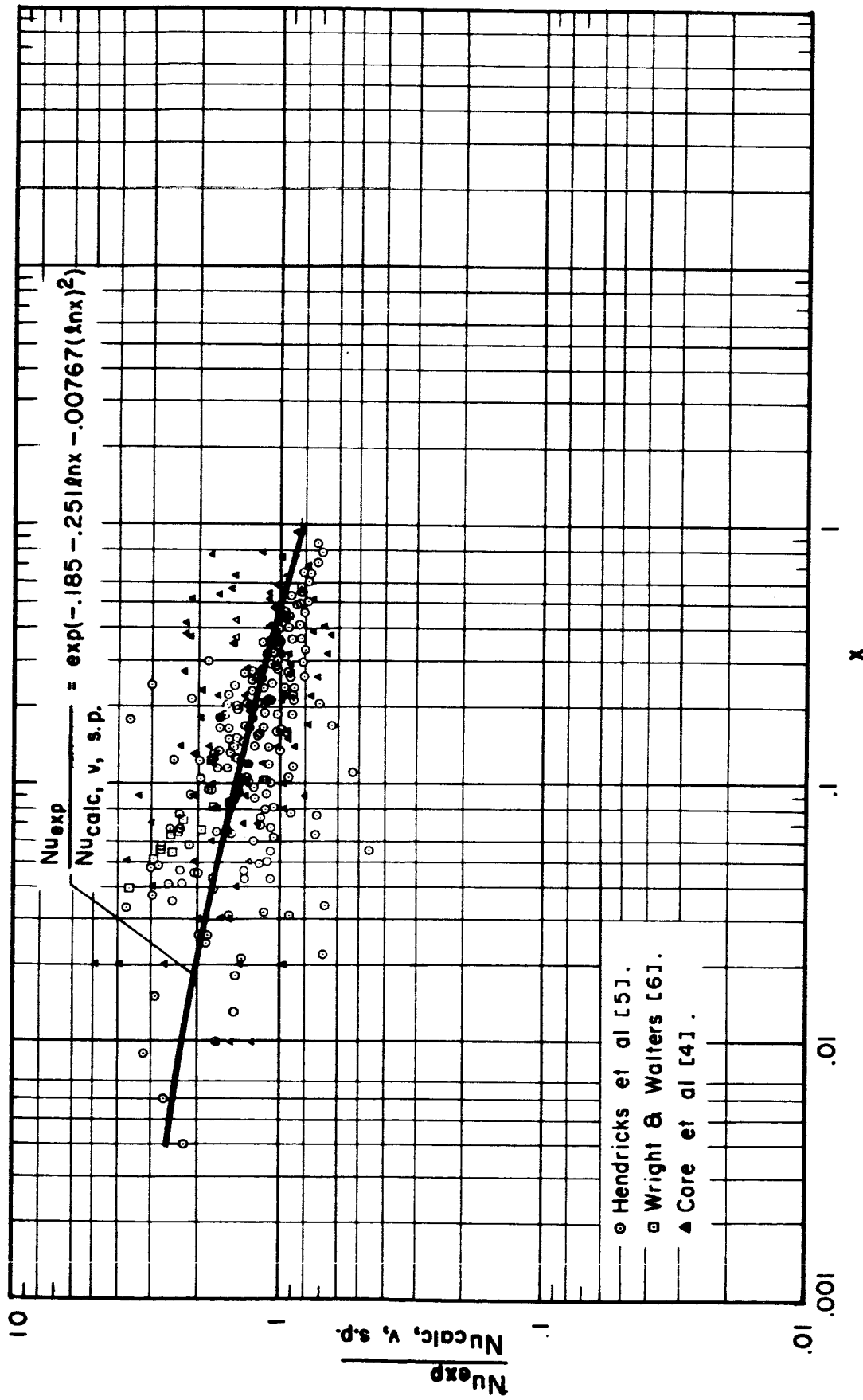


Figure 4. Single-phase Nusselt number ratio vs  $x$ (quality)

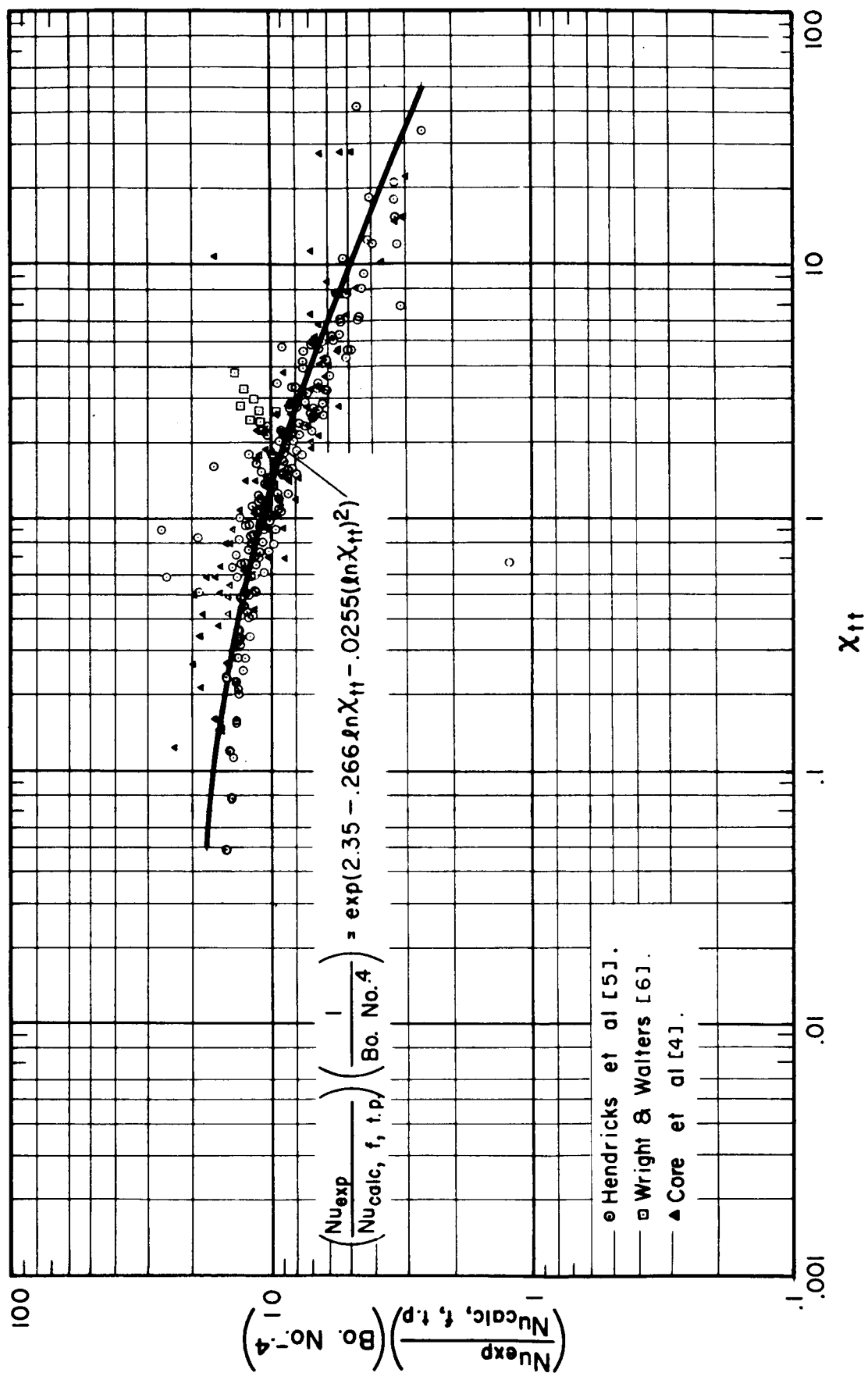


Figure 5. Two-phase Nusselt number ratio times boiling number factor vs  $X_{tt}$

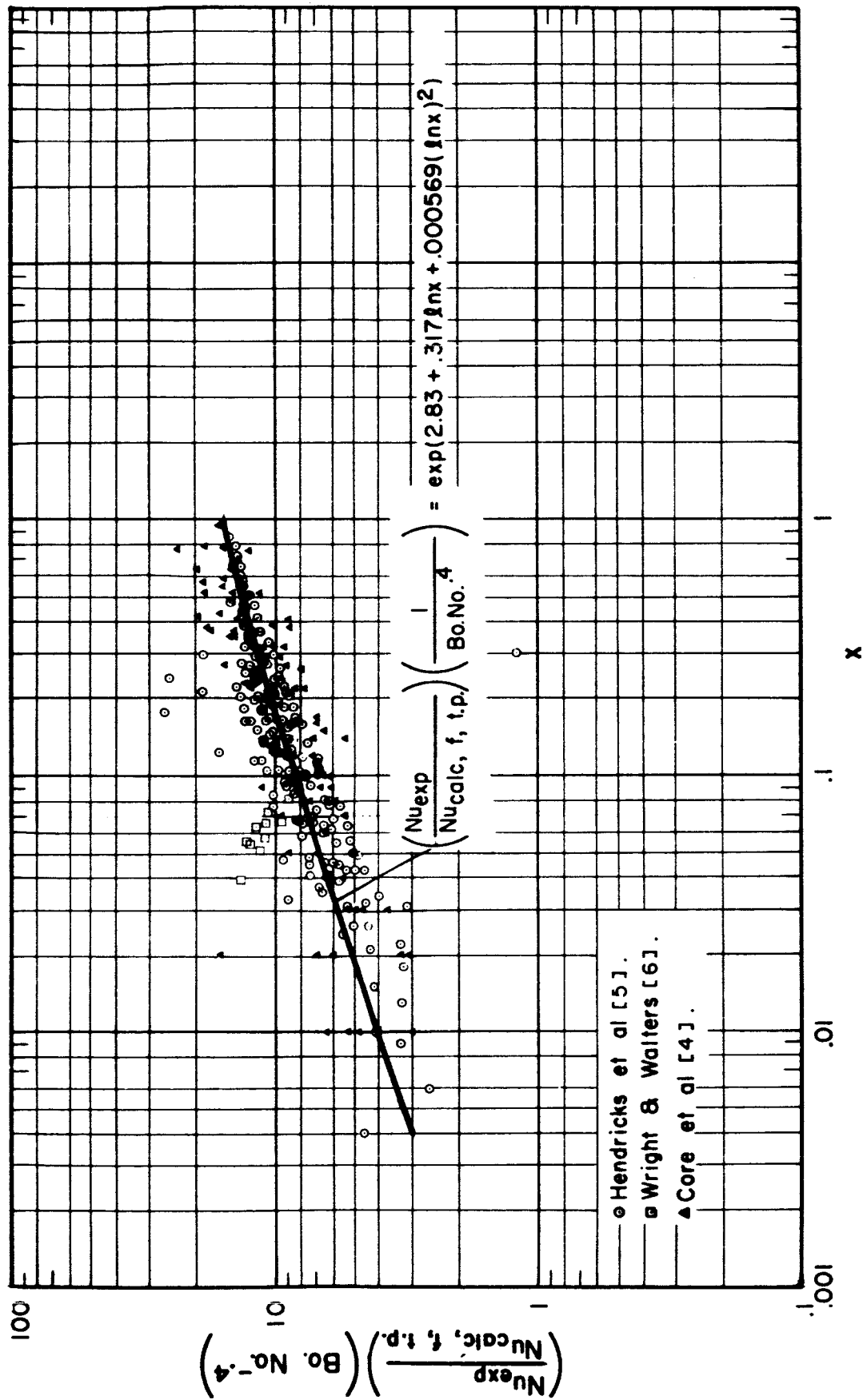


Figure 6. Two-phase Nusselt number ratio times boiling number factor vs x(quality)

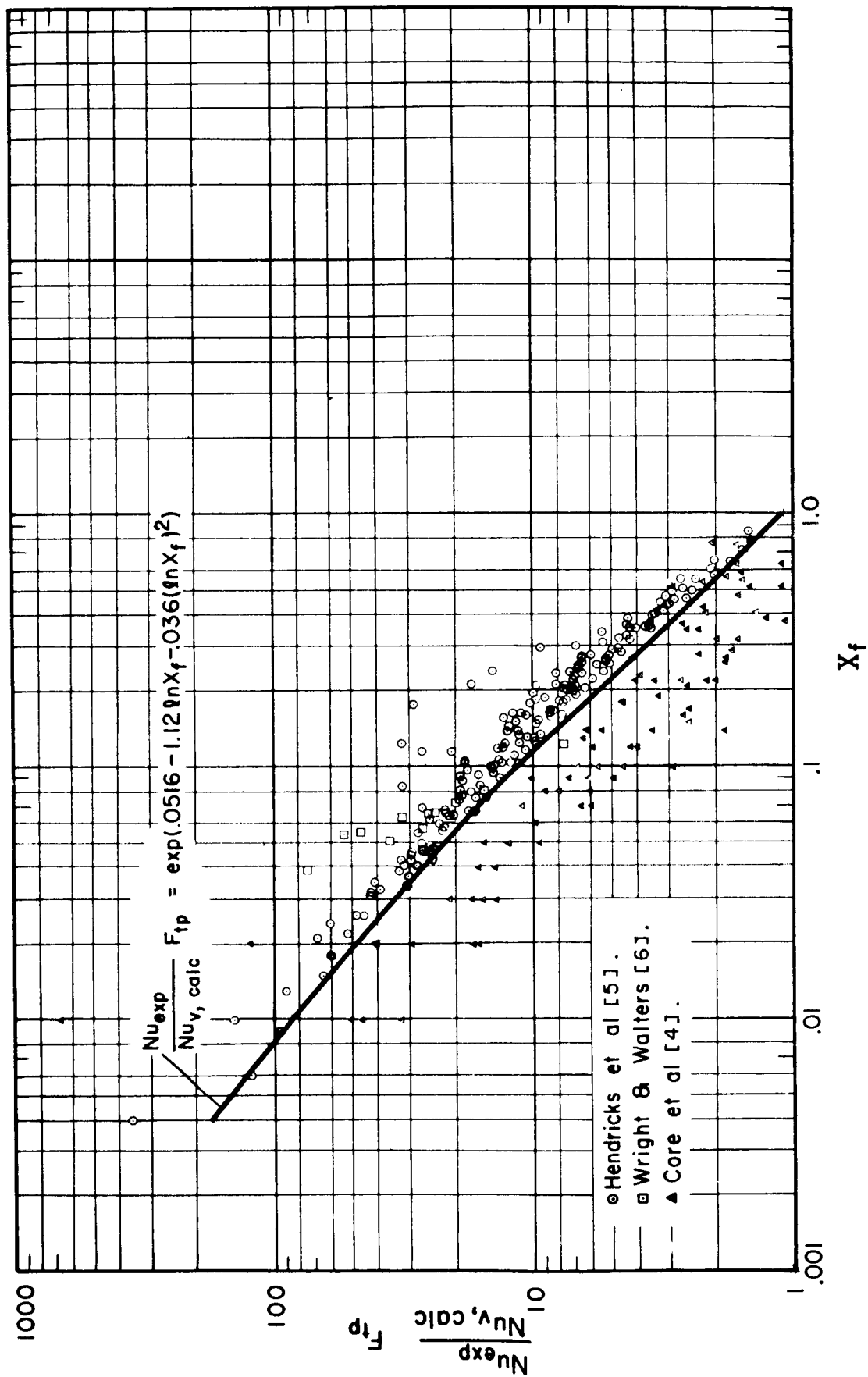


Figure 7. vonGlahn Nusselt number ratio times two-phase correlation factor vs film vaporization parameter,  $X_f$



TABLE III. SUMMARY OF RESULTS  
FILM BOILING CORRELATIONS

Authors	Correlation	Least Squares Fit Curve (All Data) Y = quantity on left side of equal sign in correlation column	Least Squares Fit Curve (Hendricks, et al. Data Only) Y = quantity on left side of equal sign in correlation column	Root Mean Square Fractional Deviation, d (Hendricks, et al. Data Only)	No. of Data Points (Hendricks, et al. Data Only)
Hendricks, Graham, Hsu, and Friedman [5]	$\frac{Nu_{exp}}{Nu_{calc, f, t, p}} = f(x_t)$	$ln Y = (0.0527 - 0.416 ln x_t - 0.008 (ln x_t)^2)$	$ln Y = (-0.122 - 0.393 ln x_t - 0.0142 (ln x_t)^2)$	0.605	281
This Study	$\frac{Nu_{exp}}{Nu_{calc, f, t, p}} = f(x)$	$ln Y = (1.11 + 0.771 ln x + 0.0571 (ln x)^2)$	$ln Y = (0.848 + 0.654 ln x + 0.0371 (ln x)^2)$	0.584	281
This Study	$\frac{Nu_{exp}}{Nu_{calc, v, s, p}} = f(x_t)$	$ln Y = (0.222 + 0.160 ln x_t - 0.008 (ln x_t)^2)$	$ln Y = (0.193 + 0.164 ln x_t - 0.0232 (ln x_t)^2)$	0.446	281
This Study	$\frac{Nu_{exp}}{Nu_{calc, v, s, p}} = f(x)$	$ln Y = (-0.185 - 0.251 ln x - 0.00767 (ln x)^2)$	$ln Y = (-0.324 - 0.334 ln x - 0.0263 (ln x)^2)$	0.414	281
Ellerbrock, Livingood, and Straight [7]	$\left( \frac{Nu_{exp}}{Nu_{calc, f, t, p}} \right) \left( \frac{1}{Bo. No.} - 0.4 \right) = f(x_t)$	$ln Y = (2.35 - 0.266 ln x_t - 0.0255 (ln x_t)^2)$	$ln Y = (2.32 - 0.257 ln x_t - 0.040 (ln x_t)^2)$	0.209	272
This Study	$\left( \frac{Nu_{exp}}{Nu_{calc, f, t, p}} \right) \left( \frac{1}{Bo. No.} - 0.4 \right) = f(x)$	$ln Y = (2.83 + 0.317 ln x + 0.000569 (ln x)^2)$	$ln Y = (2.77 + 0.256 ln x - 0.0166 (ln x)^2)$	0.240	272
von Glahn [8]	$\frac{Nu_{exp}}{Nu_{v, calc}} F_{tp} = f(x_t)$	$ln Y = (0.0516 - 1.12 ln x_t - 0.036 (ln x_t)^2)$	$ln Y = (0.258 - 1.18 ln x_t - 0.0506 (ln x_t)^2)$	0.681	281
This Study*	$h_{pred} = h_{conv, s, p, v} + h_{fill, pool}$	Not applicable	Not applicable	0.482	281

\* Basic idea of superposition is quite old. Variations are in expressions for the convective and pool boiling heat transfer coefficients.

TABLE III. SUMMARY OF RESULTS (continued)

## NUCLEATE BOILING CORRELATIONS

Authors	Correlation	Least Squares Fit Curve (All Data) Y = quantity on left side of equal sign in correlation column	Least Squares Fit Curve (Hendricks, et al. Data Only)	Root Mean Square Fractional Deviation, $\bar{d}$ (Hendricks, et al. Data Only)	No. of Data Points
Chen [11]	$h_{pred} = h_{fc} F + h_{f-z} S$	Not applicable	Not applicable	0.417 -	19 Data points used Wright and Walters data only
Kutateladze [13]	$h_{pred} = \left( h_{s.p.l}^{conv} \right) \cdot \sqrt{1 + \left( \frac{h_{nucleate\ 2}}{h_{s.p.l}^{conv}} \right)}$	Not applicable	Not applicable	0.338 -	19 Data points used Wright and Walters data only
This Study *	$h_{pred} = h_{s.p.l}^{conv} + h_{nucleate\ pool\ boil}$	Not applicable	Not applicable	0.400 -	19 Data points used Wright and Walters data only

\* Basic idea of superposition is quite old. Variations are in expressions for the convective and pool boiling heat transfer coefficients.

then calculated for each experimental data point.

- (3) As a means of comparing the relative success or failure of the correlations for the data considered, a root mean square fractional deviation,  $\underline{d}$  of the predicted value  $h_{pred}$  from the measured value,  $h_{exp}$  was determined.  $\underline{d}$  is defined as

$$\underline{d} = \sqrt{\frac{\sum_{i=1}^n [(h_{pred_i} - h_{exp_i})/h_{exp_i}]^2}{n}} \quad (37)$$

where  $n$  is the number of data points.

If the data population followed a normal distribution pattern,  $\pm \underline{d}$  would be the spread within which about 68% of the data occur and  $\pm 2\underline{d}$  would be the spread within which about 95% of the data are found. Even if the distribution varies considerably from normal it is felt that  $\underline{d}$  may be used as a measure of the relative reliability of the correlations.

## DISCUSSION

### $\chi_{tt}$ and $x$ Correlations without Boiling Number

The first four correlations shown in Table III may be generally considered together. The  $\chi_{tt}$  correlations are based on a supposed analogy between heat and momentum transport. This system has been

used extensively (Guerrieri and Talty [14], Dengler and Addoms [15], Hendricks, et al. [5]) and a further use of the analogy between momentum and mass transport has been proposed and used (Wicks III, and Dukler [16]). It would appear, however, for hydrogen that  $x$  is the controlling factor in  $\chi_{tt}$  and that a correlation with  $x$  might be simpler and just as satisfactory.

The means of computing Reynolds number varied with the investigators. Hendricks, et al. [5] use a mean film density with the average velocity of the mixture and the viscosity of the gas evaluated at the mean

film temperature  $\left( \frac{\rho_{f, m. t. p} U_{avg} D}{\mu_{f, v}} \right)$  and von Glahn [8] evaluates the

Reynolds number using the saturated vapor properties and the mass

velocity of the mixture  $\left( \frac{DG_{mix}}{\mu_v} \right)$ . Since for film boiling the process

is visualized as heat transfer through a vapor film to a liquid or liquid-vapor core, it was felt that perhaps a single-phase gas Reynolds number

$\left( \frac{\rho_v U_{avg} D}{\mu_v} \right)$  rather than the two-phase gas Reynolds number

$\left( \frac{\rho_{f, m, t. p.} U_{avg} D}{\mu_{f, v}} \right)$  used in the calculation of Nusselt number might

also produce a successful correlation. All of these considerations (except the von Glahn approach) variously combined have produced the first four correlations shown in figures 1 through 4. The  $\underline{d}$  values for these

correlations indicate that for these data the simpler system of figures 3 and 4 has provided the best correlation. This is not true when the data of Hendricks, et al. [5] are used alone. It appears then, that for hydrogen, accuracy is not lost by the use of quality rather than  $\chi_{tt}$  as a correlating parameter and may not be lost by use of the single-phase gas at average velocity in the determination of the calculated Nusselt number.

#### $\chi_{tt}$ and x Correlations with Boiling Number

Several investigators (Schrock and Grossman [17]; Ellerbrock, et al.[7]) have found that by use of the boiling number the correlations have been markedly improved. Figure 8, which is a plot of

$\frac{Nu_{exp}}{Nu_{calc, f, t. p.}}$  vs  $\chi_{tt}$  for some of the data of Hendricks, et al. shows, for

example, how the data tend to separate according to boiling number.

Thus, as shown in figure 5, when the ratio  $\frac{Nu_{exp}}{Nu_{calc, f, t. p.}}$  is multiplied

by  $(Bo. No.)^{-0.4}$ , the correlation is improved. The improvement in d values is quite significant, reducing the data spread by a factor of 3 for all the data but less for the Hendricks, et al. data alone. Perhaps an explanation for the effectiveness of the boiling number in the correlation is that this provides a measure of the ratio of the velocity of the vapor formed to the normal stream velocity. It seems quite conceivable that this ratio would have a considerable effect on the flow pattern and subsequently on the heat transfer coefficient. No plots are shown using the

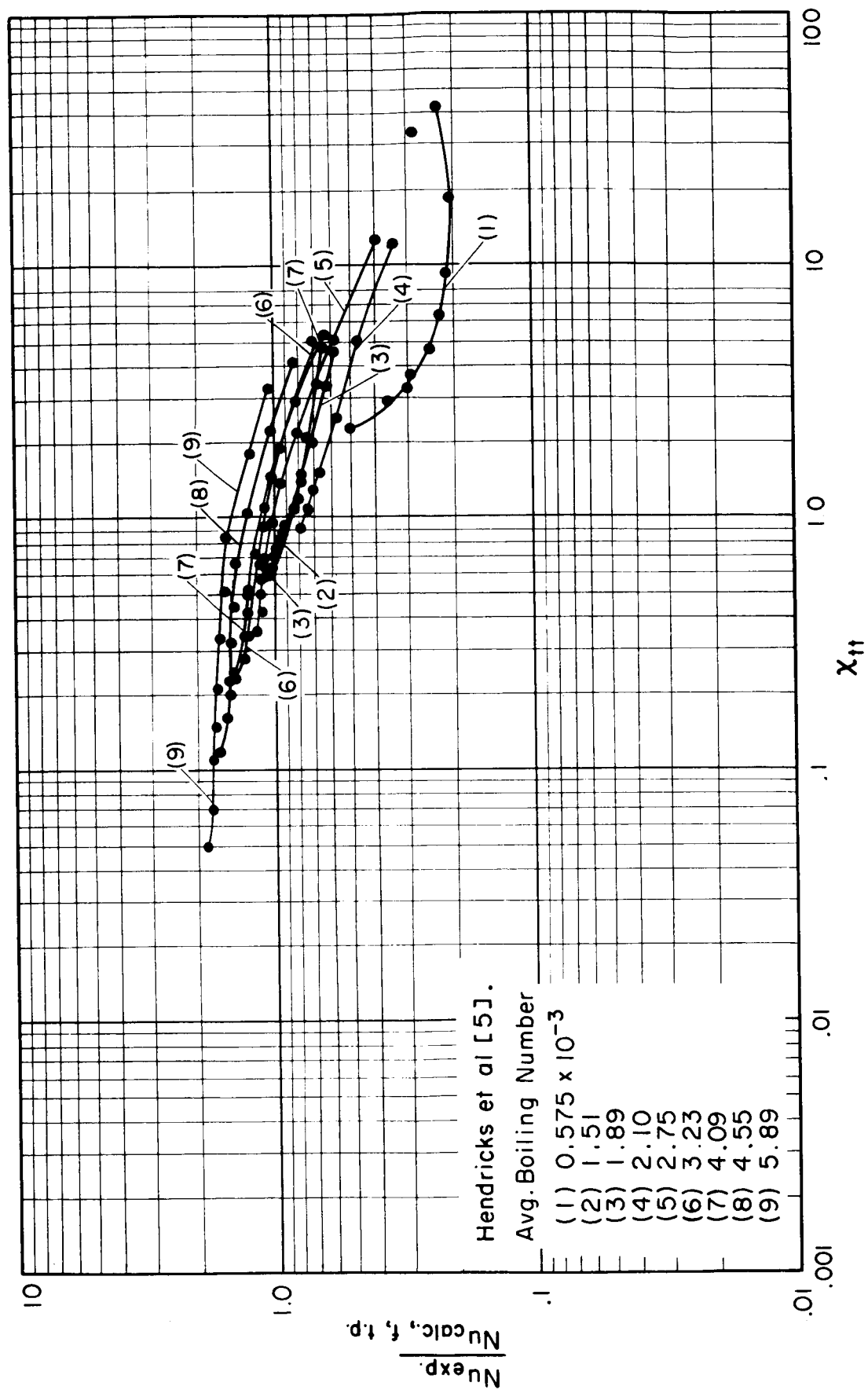


Figure 8. Two-phase Nusselt number ratio vs  $X_{tt}$  for Hendricks, et al. only illustrating separation of data according to boiling number

boiling number with the single-phase Nusselt number ratio as it would have been necessary to make appropriate changes in the exponent on the boiling number to optimize the fit using that Nusselt number ratio.

A disadvantage of the boiling number correlation for design purposes is that the heat flux must be known in order to use the correlation.

#### von Glahn Correlation

The value of  $\underline{d}$  for the correlation proposed by von Glahn [8] is relatively high when all three sets of data are considered. The best curve fit for this correlation given in Table III was determined from figure 7 which shows the data of Hendricks, et al. [5], Wright and Walters [6], and Core, et al. [4]. The data of Core, et al. appear to plot at a reduced slope compared with the data of Hendricks, et al. and Wright and Walters. von Glahn points out in his report that for  $0.7 < L_e/D < 3.5$  such a reduced slope was obtained when the exponent  $\underline{a}$  was taken to be 0.13. In this study these authors used  $\underline{a} = 0.13$  for the data of Core, et al. The dimension  $L_e$  was not recorded, but figure 4, Appendix I of Core's report, indicates an  $L_e/D$  ratio  $> 3.5$ . However, it is conceivable that  $L_e/D$  for Core's test section was in fact less than 3.5 which may account for the reduced slope plot of their data which subsequently would produce a higher  $\underline{d}$  value for von Glahn's correlation. For the Hendricks, et al. [5] data alone, the von Glahn correlation compares favorably with the boiling number correlation. Like the boiling number correlation, the von Glahn correlation requires a knowledge of the heat flux in order to determine  $F_{tp}$ .

Another consideration present in the von Glahn correlation is that the correlating parameters were developed using both hydrogen and nitrogen data and further tested for applicability to Freon 113. Since these fluids present wider ranges of property data one might conclude that this correlation may be used over a greater range than those developed for hydrogen data only. This would be true, however, only if the properties data are accounted for properly. It may be open to question whether or not any of the correlations used in this study have reached that degree of development.

#### Film Boiling Superposition

The superposition approach is an extremely simple one, and its  $\bar{h}$  value calculated on the basis of all three sets of data indicates that it is comparable to the other film boiling correlations. Since the superposition approach does not consider any of the interactions of the boiling and convective heat transfer mechanisms which would appear to be present and significant, the comparable success of this correlation leaves doubt as to whether any of the other film boiling correlations of this study have properly accounted for such interrelationship.

#### Nucleate Boiling Correlations

It might be noted here that some researchers have proposed use of the pool boiling equations alone for the forced convection boiling case. In a review paper Zuber and Fried [18] report the following in this



category:

- (1) Kutateladze [ 10]
- (2) Michenko [ 19]
- (3) Gilmour [ 20]
- (4) Labountzov [ 21]
- (5) Forster and Grief [ 22]

The forced convection contributions for the data of this study, however, were significant and varied; on this basis it is assumed that the use of the boiling component alone would constitute a relatively poor predictive system.

For the limited data considered, correlations applied for nucleate boiling appear to be as good as or better than the film boiling correlations.

All three of the nucleate boiling predictive equations employ a superposition approach but the correlation of Chen does attempt to account for the interaction of the boiling and convective heat transfer mechanisms by the factors  $\underline{F}$  and  $\underline{S}$ . However, the  $\underline{d}$  values indicate that the simple superposition equation and Kutateladze's equation, neither of which attempts to account for these interactions, are just as successful in correlating the data used in this study. Unfortunately, limited data from only one source (Wright and Walters [ 6]) were available for this comparison.

## CONCLUSIONS

The general conclusions of this study are:

- (1) Within the range of fluid property variables and systems

of the data of this study, the boiling number correlation, (5) and (6), appears to be more successful in predicting heat transfer coefficients in the film boiling region. However, for design purposes, little accuracy is lost by using the simpler systems such as the correlation using the Nusselt number ratio versus quality (2). It may be that further simplification such as the use of single-phase properties in determining the Nusselt number (calc) for the correlations vs  $x$  and  $\chi_{tt}$ , and use of the superposition method, (8), will not result in an objectionable loss of accuracy. The use of all data considered in this report indicates this to be true, but the use of the Hendricks, et al. [5] data alone indicates a somewhat greater loss in accuracy for the simpler systems.

Correlations for the nucleate boiling region (9), (10), and (11) generally are better than the film boiling correlations, but on the basis of the small number of data points available for consideration, these results are not considered very significant. The Kutateladze approach (11), appears to be the better of the nucleate boiling correlations.

- (2) The conditions at which properties are to be evaluated and the interrelationship between boiling and forced convection phenomena is quite different in all of the correlations of this study. Yet their reliability as evidenced by the d values is generally the same; it would appear that all

systems of approach are lacking in treatment of the significant variables.

- (3) The predictability of the systems of this study does not appear to fall in a respectable range for correlation, but certainly for a thorough test more experimental data are needed. Further work should be in the direction of a more fundamental analytical study of the fluid mechanics and heat transfer phenomena and the acquiring of data from very carefully controlled, experimental systems.

# NOTATION

$C_p$	=	specific heat capacity at constant pressure, joules/g-K
$\underline{d}$	=	root mean square deviation, dimensionless
$D$	=	inside diameter of tube, cm
$F$	=	correction factor which is a function of $x_{tt}$ and accounts for increased convective turbulence due to the presence of vapor
$F_{tp}$	=	von Glahn two-phase modification factor, dimensionless
$g$	=	acceleration of gravity, $\text{cm/sec}^2$
$G$	=	mass velocity, $\text{g/sec-cm}^2$
$h$	=	coefficient of heat transfer, $\text{W/cm}^2\text{-K}$
$h_{\text{conv s.p. } \ell}$	=	single-phase liquid convective heat transfer coefficient, $\text{W/cm}^2\text{-K}$
$h_{\text{conv s.p. } v}$	=	single-phase vapor convective heat transfer coefficient, $\text{W/cm}^2\text{-K}$
$h_{fc}$	=	forced convection heat transfer coefficient from Chen's correlation, $\text{W/cm}^2\text{-K}$
$h_{f-z}$	=	pool boiling heat transfer coefficient from Chen's correlation, $\text{W/cm}^2\text{-K}$
$h_{\text{film pool boil}}$	=	film pool boiling heat transfer coefficient, $\text{W/cm}^2\text{-K}$
$h_{\text{nucleate pool boil}}$	=	nucleate pool boiling heat transfer coefficient, $\text{W/cm}^2\text{-K}$

$k$	=	thermal conductivity, $\text{W}/\text{cm}^2\text{-K}$
$L_e$	=	sum of distance $y$ and unheated upstream hydrodynamic portion of tube, where $y$ is the critical length measured from beginning of heated portion of tube to burnout location, cm
$\dot{m}$	=	mass flow rate, g/sec
$N_{\text{bo. no.}}$	=	von Glahn correlation boiling number, dimensionless
$Nu$	=	Nusselt number, dimensionless
$Nu_{\text{calc, f, t. p.}}$	=	two-phase calculated Nusselt number with vapor properties evaluated at the film temperature $\frac{T_w + T_l}{2}, \text{ dimensionless}$
$Nu_{\text{calc, v, s. p.}}$	=	single-phase calculated Nusselt number with vapor properties evaluated at saturation conditions, dimensionless
$Nu_{\text{v, calc}}$	=	von Glahn calculated Nusselt number with vapor properties evaluated at saturation conditions, dimensionless
$P$	=	pressure of the boiling system, $\frac{\text{dynes}}{\text{cm}^2}$
$Pr$	=	Prandtl number, dimensionless
$q$	=	rate of heat transfer per unit area $\frac{\text{W}}{\text{cm}^2}$
$Re_{\text{f, m, t. p.}}$	=	two-phase Reynolds number based on the average velocity of the mixture and with vapor viscosity evaluated at mean film conditions, dimensionless

- $Re_{\ell}$  = two-phase Reynolds number based on the average velocity of the mixture and with liquid viscosity evaluated at bulk saturation conditions, dimensionless
- $Re'_{\ell}$  = single-phase Reynolds number based on the average velocity of the mixture and with liquid viscosity evaluated at bulk saturation conditions, dimensionless
- $Re_v$  = two-phase Reynolds number based on the average velocity of the mixture and with vapor viscosity evaluated at bulk saturation conditions, dimensionless
- $Re_{v, s. p.}$  = single-phase Reynolds number based on the average velocity of the mixture and with vapor viscosity evaluated at bulk saturation conditions, dimensionless
- $S$  = correction factor which is a function of  $Re'_{\ell} F^{1.25}$  and accounts for suppression of bubble growth due to flow, where  $Re'_{\ell} = \frac{DG_{mix}(1-x)}{\mu_{\ell}}$
- $\Delta T$  =  $T_w - T_{\ell}$ , K
- $U_{avg}$  = average fluid velocity,  $\frac{cm}{sec}$
- $x$  = quality, dimensionless
- $x_c$  = thermodynamic fluid quality at burnout location, dimensionless

$x_f$	=	quality in film boiling regime, dimensionless
$X_f$	=	film boiling vaporization parameter, dimensionless
$\alpha, \beta, \gamma, \Gamma$	=	von Glahn film boiling correlation parameters, dimensionless
$\lambda$	=	latent heat of vaporization at saturation, $\frac{\text{joules}}{\text{g}}$
$\lambda'$	=	"effective" latent heat of vaporization, $\frac{\text{joules}}{\text{g}}$
$\mu$	=	Newtonian coefficient of viscosity, $\frac{\text{g}}{\text{cm sec}}$
$\rho$	=	density, $\frac{\text{g}}{\text{cm}^3}$
$\Delta\rho_f$	=	$\rho_l - \rho_f$ , $\frac{\text{g}}{\text{cm}^3}$
$\rho_{f,m,t.p.}$	=	two-phase mean film density, $\frac{\text{g}}{\text{cm}^3}$
$\Delta\rho_v$	=	$\rho_l - \rho_v$ , $\frac{\text{g}}{\text{cm}^3}$
$\sigma$	=	surface tension between the liquid and its own vapor, evaluated at $T_l$ , $\frac{\text{dynes}}{\text{cm}}$
$\chi_{tt}$	=	Martinelli parameter, dimensionless
<u>Subscripts</u>		
avg	=	average
b	=	indicates bulk property
exp	=	indicates the subscripted h or Nu is the experimental value

f or f,v = Indicates that the subscripted vapor property is to be  
 evaluated at the vapor film temperature,  $(1/2) (T_w + T_\ell)$

$\ell$  = indicates that the subscripted liquid property is to be  
 evaluated at the saturation temperature of the boiling  
 fluid

mix = mixture

pred = indicates the subscripted h is the predicted value

t. p. = indicates two-phase

v = indicates that the subscripted vapor property is to be  
 evaluated at the saturation temperature of the boiling  
 fluid

w = indicates that the subscripted property is to be evaluated  
 at the temperature of the heater surface



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