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A new correlation for heat transfer during flow boiling

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A NEW CORRELATION FOR HEAT TRANSFER DURING FLOW BOILING

by

Bhabesh K. Thakur

A Thesis Submitted
in
Partial Fulfillment
of the
Requirements for the Degree of
MASTER OF SCIENCE
in
Mechanical Engineering

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ABSTRACT

This thesis is concerned with an investigation carried out to establish a new correlation for the prediction of the heat transfer coefficient during flow boiling through tubes, vertical and horizontal flows, for water and organic fluids (including refrigerants). An additive mechanism of convective and boiling heat transfer has been formulated to give the net heat transfer during flow boiling. The correlation employs three dimensionless parameters: the Convection number, the Boiling number and the Froude number. The correlation has been tested with the data (over 500) from twelve experimental cases of six investigators and the mean deviation from the measured values of the heat transfer coefficients has been found to be $\pm 13\%$.

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NOMENCLATURE

A	Surface area through which heat is transferred.
A_c	Cross-sectional area
Bo	Boiling number q/Gh_{fg}
c_p	Specific heat at constant pressure
c_{p1}	Specific heat of the liquid phase at constant pressure
c_{pg}	Specific heat of the gas phase at constant pressure
Co	Convection number, $(1/x-1)^{0.8} (\rho_g/\rho_l)^{0.5}$
D	Diameter of pipe
F	Nucleate boiling correction factor
Fr	Froude number, V^2/gD
Fr_λ	Froude number assuming all mass flowing in liquid form
g	Acceleration due to gravity
G	Total mass flux or mass velocity, W/A_c
G_l	Mass flux of liquid phase
G_g	Mass flux of gas phase
h	Heat transfer coefficient
h_{fg}	Latent heat of vaporization
h_{TP}	Two-phase heat transfer coefficient local
h_l	Heat transfer coefficient for liquid phase
k	Thermal conductivity
Nu	Nusselt number, hD/k
p	Pressure
P_c	Critical pressure
Pr	Prandtl number, $c_p \mu/k$

q Heat flux, Q/A
 Q Total heat transferred in unit time
 Re Reynolds number, GD/ μ
 Re_l Superficial Reynolds number of liquid phase
 T Temperature
 T_{SAT} Saturation temperature
 T_f Fluid temperature
 T_w Temperature of pipe wall
 ΔT Change or difference in temperature
 $\Delta T_{SAT} = T_w - T_{SAT}$
 W Total mass flow rate
 x Weight fraction vapor
 x_{tt} Martinelli parameter $(\frac{1-x}{x})^{0.9} \quad (\rho_g/\rho_l)^{0.5} \quad (\mu_l/\mu_g)^{0.1}$
 ψ Ratio h_{TP}/h_l
 μ Viscosity
 ρ Density
 σ Vapor-liquid surface tension

Subscripts

g For the gaseous phase or vapor phase
 l, l For the liquid phase

Definition

$$\% \text{ Mean Error} = \frac{\text{Predicted Value} - \text{Measured Value}}{\text{Measured Value}} \times 100$$

CHAPTER 1

INTRODUCTION

The heat transfer in boiling, i.e. during change of phase from liquid to vapor, is a very efficient means of heat transfer, due to the ability of the boiling systems to attain large heat fluxes, while employing relatively small temperature differences. This mode of heat transfer is applied in numerous industrial systems, such as, boilers in steam power plants, equipments in air-conditioning and refrigeration systems, and nuclear reactors.

There are basically two types of boiling; (i) pool boiling, and (ii) flow boiling:

(i) Pool boiling: The pool boiling is the boiling on a heated surface submerged in a pool of stagnant liquid. There are three regimes observed in pool boiling - (a) nucleate boiling, (b) transition boiling, and (c) film boiling - and each occurs over a range of superheat (temperature exceeding saturation temperature).

(ii) Flow boiling: When a liquid flows in a heated tube, heat transfer takes place by single phase forced convection. As the bulk fluid temperature reaches a level somewhat below the saturation temperature, subcooled boiling may occur at the tube

wall. Finally, when the bulk fluid temperature reaches the saturation temperature, saturated boiling commences and net vapor generation takes place in the flow stream. From this point to the point where all the liquid has been converted to vapor, the two-phase bulk fluid temperature continuously decreases. Within the boiling region of the tube, several complex interacting processes occur simultaneously:

(a) Heat is transferred from the tube wall into the two-phase mixture, the net effect of this heat transfer being the formation of vapor. It is not conclusively known whether the vaporization mechanism resembles that of nucleate boiling or if there is some other mechanism.

(b) Vapor is also formed by flashing because of the pressure drop and the criteria of the thermal equilibrium between phases. The exact mechanism of this vaporization process is also not known.

(c) There are large two-phase-flow friction losses. From many experimental studies, it is well known that frictional pressure losses for two-phase flows are usually very large in comparison with those obtained in ordinary single-phase turbulent flows. The increase in pressure drop is due to two reasons described below:

i) The generation of vapor leads to large pressure losses.

With the generation of vapor, the overall specific volume of the two-phase mixture increases, with a resultant increase in the overall flow velocity.

(ii) The acceleration due to vapor formation has the added effect of increasing flow velocities and turbulent mixing. Both of these situations tend to increase pressure losses and heat transfer coefficients.

Flow boiling is very complex in nature; as several physical quantities and hydrodynamic conditions influence the flow boiling in a confined channel. Many empirical correlations, based on experimental results, have been suggested by many investigators for different orientations and different fluids. However, none of these empirical correlations give satisfactory results for all the fluids.

The intent of this project is to attempt to establish a satisfactory correlation for the prediction of the heat transfer coefficient during flow boiling through tubes, vertical and horizontal, on the basis of the available published experimental data.

CHAPTER 2

LITERATURE SURVEY

A. Flow Patterns: In the case of a two-phase flow in tubes, the liquid and the vapor phases are distributed in a variety of relative arrangements with respect to each other, and also with respect to the tube wall. These relative arrangements, known as flow patterns, depend upon the tube geometry, fluid properties and the operating conditions. The existing flow pattern influences the heat transfer in a two-phase flow. In order to gain a better understanding of heat transfer in two-phase flow, an adequate knowledge of flow regimes is necessary.

(i) Flow Patterns in Vertical Evaporator Upward Flow: Figure 1 shows the flow patterns for a vertical evaporator tube with upward flow. In the initial single phase region, the liquid is being heated to the saturation temperature. A thermal boundary layer forms at the wall and a radial temperature gradient is set up. As the wall temperature exceeds the saturation temperature, at some position in the tube, the condition for the formation of vapor (nucleation) at the wall is satisfied. Vapor nucleation takes place at preferred sites on the surface of the tube. Vapor bubbles grow from these sites finally detaching to form a bubbly flow. With the production of more vapor, the bubble population increases along the length and coalescence takes place to form slug flow, which in turn gives way to annular flow further along the tube. Close to this point, the formation of vapor at the sites on the wall may cease and further vapor formation may take place as a result of evaporation at the liquid film-vapor core interface.

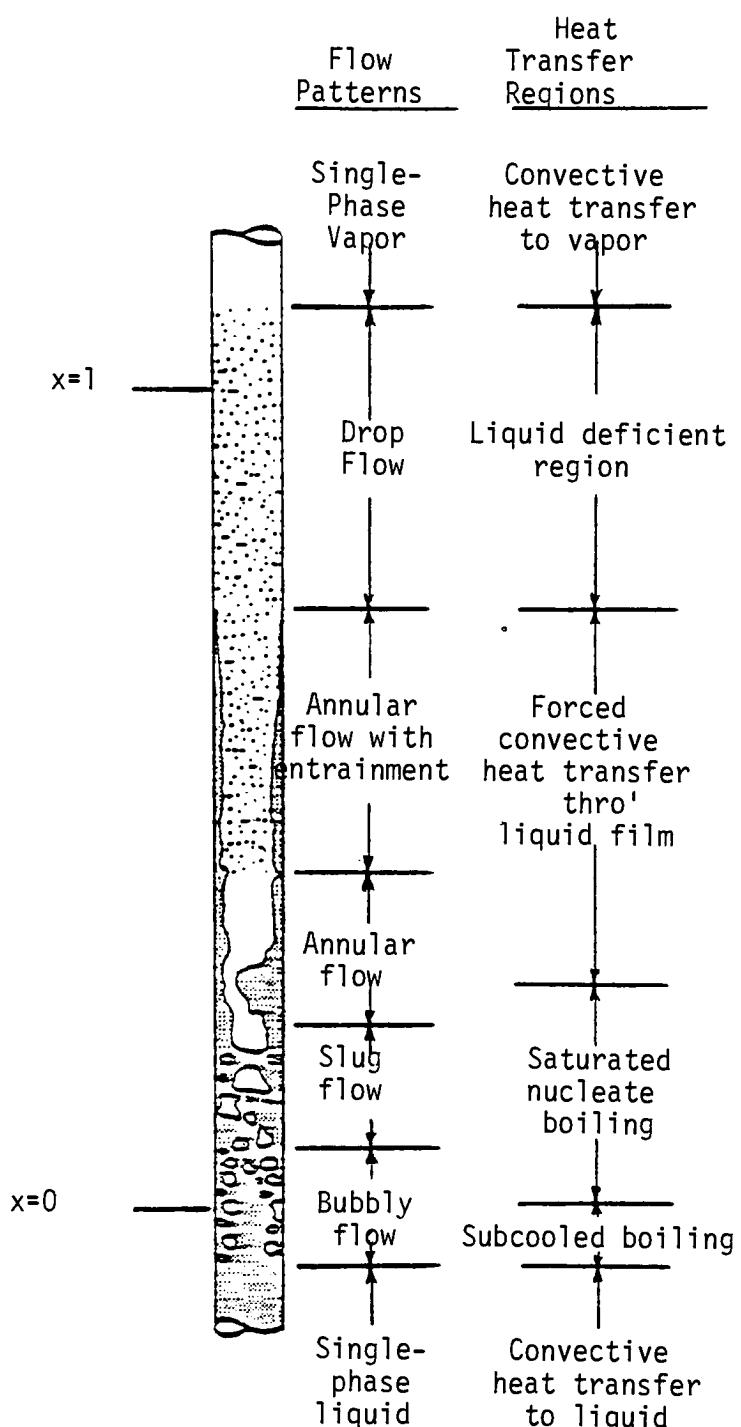


Fig. 1: Flow Patterns in a Vertical Evaporator Tube
Upward Flow, Collier

Increasing velocities in the vapor core causes entrainment of liquid in the form of droplets. The depletion of the liquid from the film by this entrainment and by evaporation finally causes the film to dry out completely. Droplets continue to exist and are slowly evaporated until only single-phase vapor is present.

(ii) Flow Patterns in Vertical Evaporator Downward Flow: The downward bubbly flow structure is quite different from the upward bubbly flow configuration. In the latter case bubbles are spread over the entire tube cross section, whereas in the downward flow, bubbles gather near the tube axis. (See Figure 2.) When the vapor flow rate is increased, the liquid flow rate being held constant, the bubbles agglomerate to form large vapor plugs. The top of these plugs is dome-shaped, whereas the lower extremity is flat with a bubbly zone underneath. The annular configuration can take several forms. For low liquid and vapor flow rates, a liquid film flows down the wall (falling film flow). If the liquid flow rate is higher, bubbles are entrained within the film (bubbly falling film). When liquid and vapor flow rates are increased, churn flow appears, and may evolve into a dispersed annular flow for very high vapor flow rates.

(iii) Flow Patterns in Horizontal Tube Evaporator: Flow patterns in horizontal tube evaporators are influenced by asymmetric phase distributions and stratification due to gravitational effects. Figure 3 shows a schematic representation of a horizontal evaporator heated by a low uniform heat flux, and fed with liquid just below the saturation temperature. The sequence

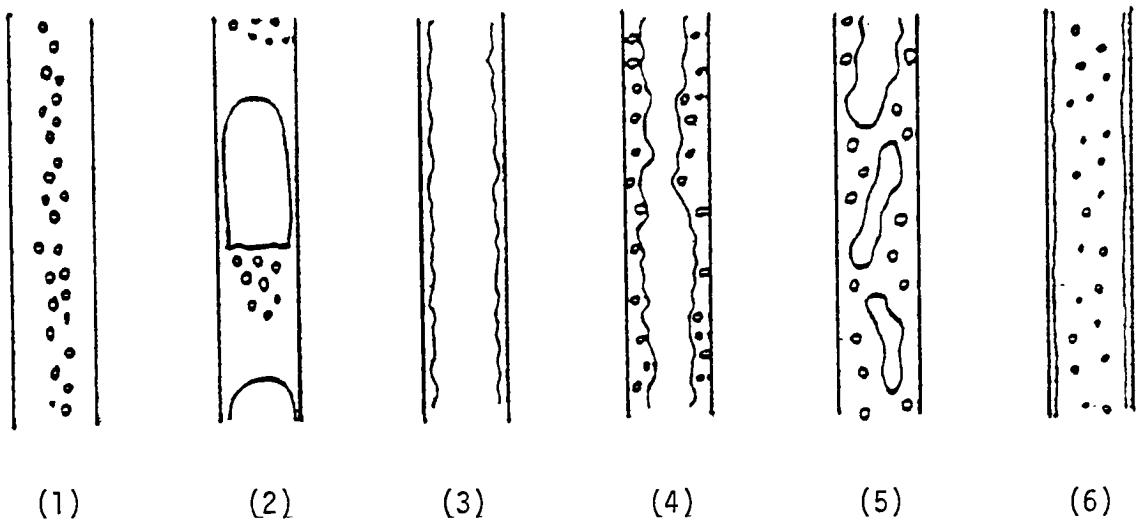


Fig. 2: Air-water flow patterns in a downward cocurrent flow in a vertical pipe, Collier¹. (1) Bubbly, (2) Slug, (3) Falling film, (4) Bubbly falling film, (5) Churn and (6) Dispersed annular flow pattern.

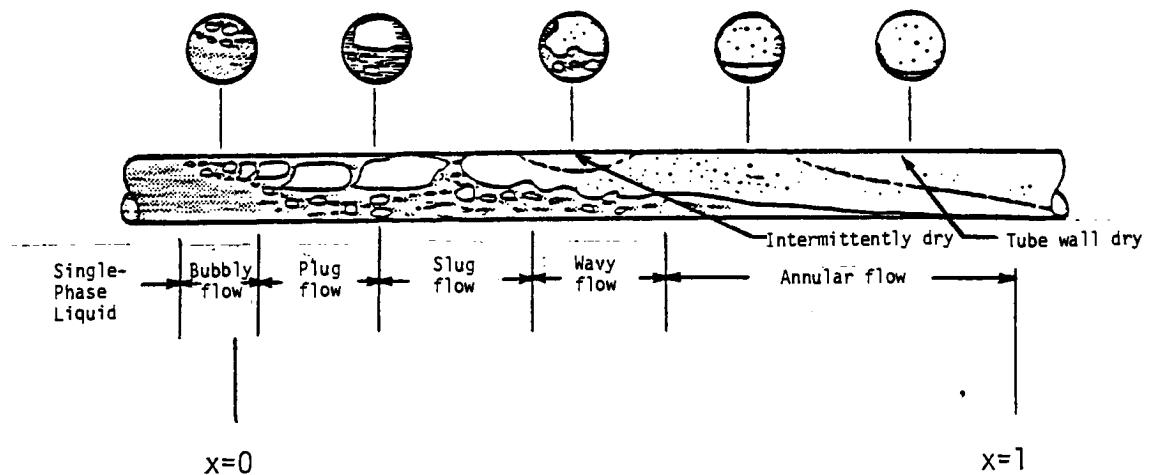


Fig. 3: Flow patterns in a horizontal tube evaporator, Collier¹.

of flow patterns shown corresponds to a relatively low inlet velocity ($< 1 \text{ m/s}$).

Important points to note from a heat transfer viewpoint are the possibility of intermittent drying and rewetting of the upper surfaces of the tube in wavy flow, and the progressive drying out of the upper circumference of the tube wall in annular flow. At higher inlet liquid velocities, the influence of gravity is less pronounced, the phase distribution becomes more symmetrical, and the flow patterns resemble those seen in vertical upward flow.

B. Existing Correlations for Flow Boiling: All the existing correlations for the prediction of heat transfer coefficient are functions of the numerous variables that influence the heat transfer in a two-phase flow. A large number of experiments have been conducted and several correlations have been proposed by previous investigators for a variety of working fluids. Some of the accepted correlations are discussed below:

i Guerrieri and Talti²: Guerrieri and Talti measured local heat transfer coefficients during upflow of various organic fluids, including cyclohexane, through vertical brass tubes whose inner surfaces had been finished by machining. The test conditions for cyclohexane were: pressure 15 psia, liquid flow velocity 1.3 - 2.8 ft/sec and heat flux $0.3 - 1.3 \times 10^4 \text{ Btu/hr-ft}^2$ and the vapor quality 2-10%. The correlation suggested by Guerrieri and Talti is as follows:

$$h_{TP} = 3.4 \left(\frac{1}{X_{tt}}\right)^{0.45} \times h_l \quad (2.1)$$

where

h_{TP} = two phase heat transfer coefficient

h_l = single phase heat transfer coefficient for liquid

X_{tt} = Martinelli parameter

The standard deviation with their own experimental data was $\pm 11.1\%$.

ii Dengler and Addoms:³

Dengler and Addoms used water in an upflow system consisting of a 1" ID 20' long, vertical copper tube. Five 3' long steam jackets were spaced along the tube and 21 thermocouples were embedded in the tube wall. Local heat fluxes were determined by collecting steam condensate from the specially designed steam jackets. Local pressure was obtained at stations between the steam jackets by a manometer system. Saturated liquid was introduced into the test section with outlet pressure ranging from 7.2 to 29 psia. Mass flux was varied from 12.2 to 280 lb_m/sec.ft². The mass vapor fraction x varied from 0 to 100%. The local volumetric vapor fraction was determined by a radio-active-tracer technique. Dengler and Addoms recommended the following correlation to represent their data:

$$h_{TP} = 3.5 \frac{F_{DA}}{(x_{tt})^{0.5}} \times h'_x \quad (2.2)$$

where, h'_x is evaluated by the Dittus-Boelter equation,

$$h'_x = 0.023 \frac{k_x}{D} \left(\frac{DG}{\mu_x} \right)^{0.8} \left(C_p \frac{\mu_x}{k_x} \right)^{0.4}$$

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

The standard deviation was $\pm 30.5\%$.

iii Bennet et al:⁴

Bennet et al made the measurements on vertical annuli upflow, the inner pipes being electrically heated. Vapor quality was generated outside the test section by mixing water with steam. The test conditions were - pressure 15-35 psia, flow velocity 0.2-0.9 ft/sec, heat flux $3.2 \times 10^4 - 1.6 \times 10^5$ Btu/hr-ft² and quality 1-59%.

Bennet et al noted an effect of heat flux and proposed the following correlation:

$$h_{TP} = 0.64 \left(\frac{1}{x_{tt}} \right)^{0.74} h_x \left(\frac{q}{A} \right)^{0.11} \quad (2.3)$$

where

$$h_{\lambda} = (1 - x)^{0.8} h'_{\lambda}$$

The standard deviation was $\pm 11.9\%$.

iv Schrock and Grossman:⁵

Schrock and Grossman used water in an upward flow system. They used electrically heated test sections of 0.1162", 0.237" and 0.4317" ID. Length varied from 15 to 40 inches. Mass fluxes varied from 197 to 911 lb_m/sec-ft² for the small tubes, and 49 - 69 lb_m/sec-ft² for the largest tube. Heat fluxes were 6×10^4 to 1.45×10^6 Btu/hr-ft² for the small tubes, and 0.65×10^5 to 2.46×10^5 Btu/hr-ft² for the largest tube. Pressure ranged from 42 to 505 psia, and exit qualities from 0% up to 59%. They introduced boiling number, Bo, as an additional variable and obtained the following correlation:

$$h_{TP} = 7400 [Bo + 1.5 \times 10^{-4} \left(\frac{1}{x_{tt}}\right)^{2/3}] h'_{\lambda} \quad (2.4)$$

where

$$h_{\lambda} = (1 - x)^{0.8} h'_{\lambda}$$

The standard deviation was $\pm 35\%$.

v Chen:⁶

Chen proposed a correlation which has been generally accepted as one of the best available. The correlation covers both the saturated nucleate boiling region and the two-phase forced convective region. It is assumed that both nucleation and convective mechanisms occur to some degree over the entire range and that the contributions made by the two mechanisms are additive.

$$h_{TP} = h_{mac} + h_{mic} \quad (2.5)$$

where h_{TP} is the local heat transfer coefficient, h_{mac} is the contribution due to convection and h_{mic} is the contribution due to nucleate boiling. h_{mac} is given by the equation:

$$h_{mac} = 0,023 \left[\frac{G(1-x)D}{\mu_l} \right]^{0.8} \rho_r^{0.4} \left(\frac{k_l}{D} \right) F \quad (2.6)$$

The parameter F is a function of the Martinelli parameter X_{tt} as shown in Fig. 4. It is approximated by the following equations:

$$F = \begin{cases} 1, & \text{for } \frac{1}{X_{tt}} \leq 0.1 \\ 2.35 \left(\frac{1}{X_{tt}} + 0.213 \right)^{0.736}, & \text{for } \frac{1}{X_{tt}} > 0.1 \end{cases} \quad (2.7)$$

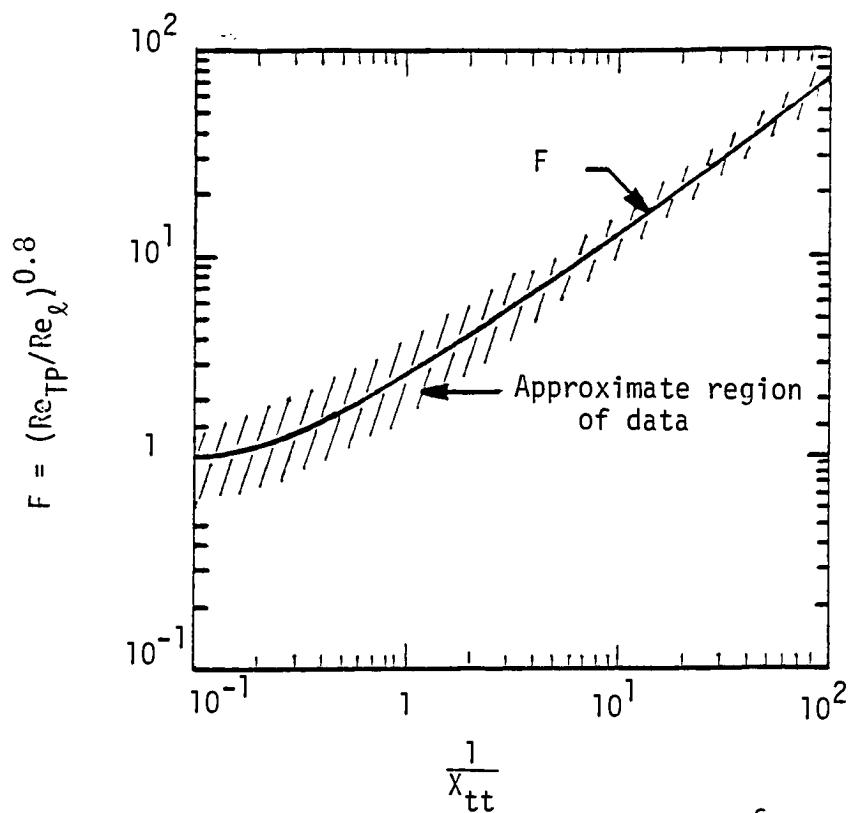


Fig. 4: Reynolds number factor, F , Chen⁶.

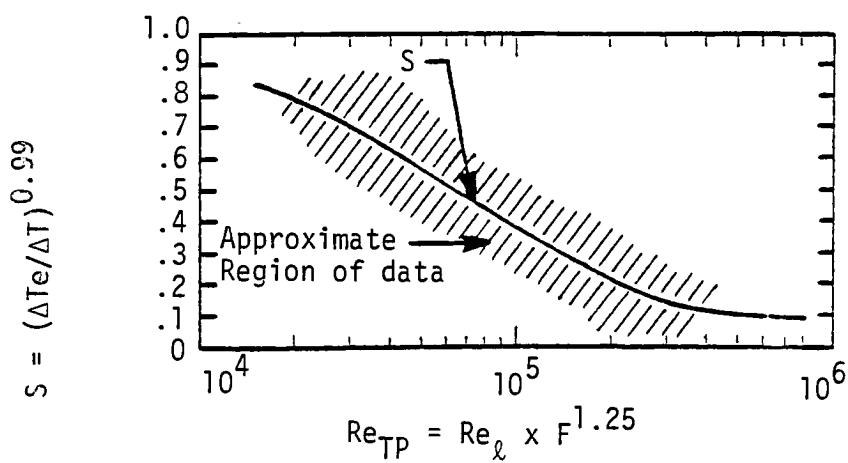


Fig. 5: Suppression factor, S , Chen⁶.

The pool boiling equation of Foster and Zuber⁷ was taken as the basis for evaluation of the nucleate boiling component, h_{mic} . The pool boiling analysis was modified to account for (a) the thinner boundary layer in forced convective boiling, and (b) the lower effective superheat that the growing vapor bubble sees. The modified Foster-Zuber equation is as follows:

$$h_{mic} = 0.00122 \frac{\frac{k_l}{\sigma}^{0.79} \frac{C_{pl}}{\mu_l}^{0.45} \frac{\rho_l}{h_{fg}}^{0.49}}{\frac{0.5}{0.29} \frac{h_{fg}}{0.24} \frac{\rho_g}{0.24}} \Delta T_{sat}^{0.24} \Delta P_{sat}^{0.75} S \quad (2.8)$$

where S is the suppression factor defined as the ratio of the mean superheat seen by the growing bubble to the wall superheat ΔT_{sat} . S is related to two-phase Reynolds number as shown in Fig. 5. It is approximated by the following equation:

$$S = 1/[1 + 2.53 \times 10^{-6} (\text{Re}_l \times F^{1.25})^{1.17}] \quad (2.9)$$

The correlation was developed using data of six different investigators for water and organic fluids. The average deviation between calculated and measured heat transfer coefficients for all (over 600) data points from ten experimental cases was $\pm 12\%$.

vi Jallouk:⁸

Jallouk carried out an extensive study of two-phase flow characteristics of refrigerants in vertical tubes. It included the

investigations on the flow regime, pressure drop, heat transfer coefficients, and critical heat flux for R-114 boiling in a 0.785 in. ID, 10 ft. long vertical tube. The saturation temperature was varied in the range of 100 - 200°F. The mass flux range was $0.12 - 3.5 \times 10^6 \text{ lb}_m/\text{hr}\cdot\text{ft}^2$. Jallouk observed that the Chen's correlation exhibited the least amount of scatter, although it consistently underpredicted the experimental heat transfer coefficient results. He proposed a variable coefficient for the Foster-Zuber pool boiling correlation for prediction of the boiling part of heat transfer. The modified h_{mic} correlation for R-114 is as follows:

$$h_{mic} = 0.3802 \frac{k_l^{0.79} c_{pl}^{0.45} \rho_l^{0.49}}{\sigma^{0.5} \mu_l^{0.29} h_{fg}^{0.24} \rho_g^{0.24}} \Delta T_{sat}^{0.24} \Delta P_{sat}^{0.75} S \quad (2.10)$$

h_{mac} is evaluated from Eq. (2.6) proposed earlier by Chen.

Majority of Jallouk's experimental values were correlated to within $\pm 30\%$.

vii Shah:⁹

Shah has developed a chart correlation, (graphical method of calculation), which appears to be considerably superior to any other available predictive technique in its range of applicability and the ease of computation. It has been compared by Shah with about 800 data points from 18 different experimental studies. These data include most of the common refrigerants in their entire range of application.

Also included are data for boiling water between 15 to 2500 psia pressure, which covers practically the entire range of boiler operation. Almost all common tube materials, horizontal and vertical orientations, circular and annular flow channels, upward and downward flow, as well as a very large range of heat and mass fluxes are covered.

The chart correlation employs four dimensionless parameters defined as follows:

$$\text{The ratio } \psi = \frac{h_{TP}}{h_\ell} \quad (2.11)$$

$$\text{Convective number } Co = \left(\frac{1}{x} - 1 \right)^{0.8} \left(\frac{\rho g}{\rho_\ell} \right)^{0.5} \quad (2.12)$$

$$\text{Boiling number } Bo = \frac{q}{Gh_{fg}} \quad (2.13)$$

$$\text{Froude number } Fr_\ell = \frac{G^2}{\rho_\ell^2 g D} \quad (2.14)$$

Froude number is calculated assuming all the mass to be flowing in liquid form. h_ℓ is calculated by the Dittus-Boelter equation.

$$h_\ell = 0.023 \left[\frac{GD(1-x)}{\mu_\ell} \right]^{0.8} Pr_\ell^{0.4} \frac{k_\ell}{D} \quad (2.15)$$

Knowing the mass flow rate, vapor quality, heat flux and pressure, Co , Bo and Fr_ℓ are easily calculated. For vertical tubes, Fr_ℓ need not be calculated. The procedure is somewhat more complex for horizontal tubes in which Fr_ℓ is less than 0.04. The use of chart for various conditions as explained by Shah for the following examples, is shown in Fig. 6.

Example 1:

Given: vertical tube

$$Co = 0.10, \quad Bo = 20 \times 10^{-4}, \quad Fr_l = 0.002$$

Solution: For vertical orientation, ignore Fr_l . Draw a vertical line at $Co = 0.1$ to intersect the curve for $Bo = 20 \times 10^4$. From this point of intersection, draw a horizontal line to the left and read ψ at the ordinate line. The solution is $\psi = 20$.

Example 2:

Given: same as example 1, but $Bo = 2 \times 10^{-4}$

Solution: Draw a vertical line at $Co = 0.1$ as before till it intersects line AB. As $Bo \times 10^4$ at this point of intersection is 4.5, the actual boiling number of 2×10^{-4} has no influence. Draw a horizontal line from point of intersection to the ordinate line. The solution is $\psi = 11$.

Example 3:

Given: Same as example 1, but the tube is horizontal.

Solution: Draw a vertical line from $Co = 0.1$. From the point where it intersects the line for $Fr_l = 2 \times 10^{-3}$, draw a horizontal

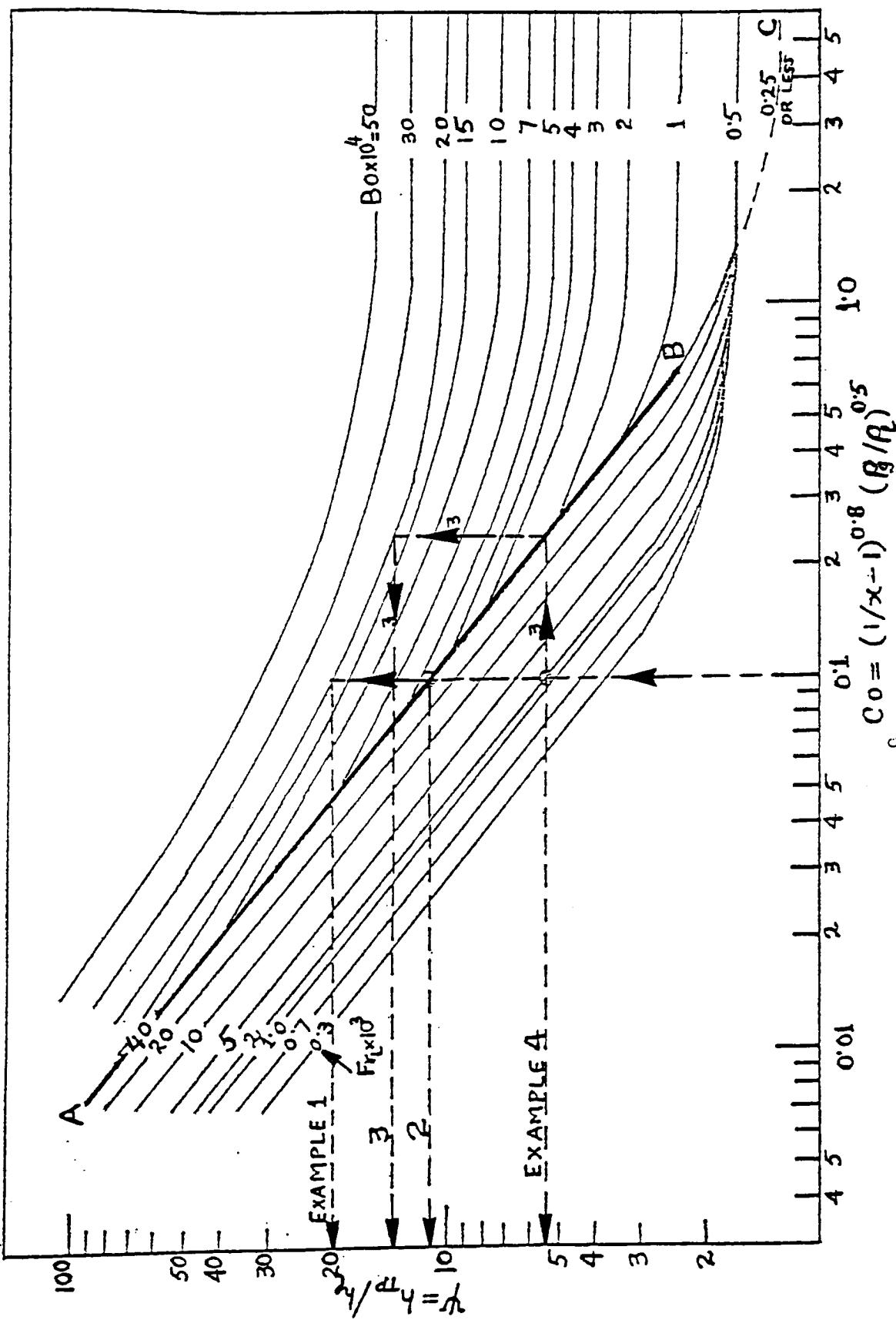


Fig. 6: Chart Correlation of Shah^S, showing Examples 1-4.

line to the right to intersect the line AB. From this point of intersection draw a vertical line to intersect the curve for $Bo = 20 \times 10^{-4}$. Draw a horizontal line from this last point of intersection to the left to intersect the ordinate. The solution is $\psi = 14$.

Example 4:

Given: Same as example 2, but the tube is horizontal.

Solution: Proceed as in Example 3 till the line AB is intersected. As this point of intersection is above the point where the curve for $Bo = 2 \times 10^{-4}$ intersects the line AB, Bo has no influence. Draw a line to the left to read ψ . The solution is $\psi = 5.4$.

Shah has analyzed over 750 data points from 17 sources. These include a pressure range of 15 to 200 psia, circular and annular flow geometries, as well as vertical and horizontal flow orientations. Ninety percent of the data are correlated to within $\pm 30\%$ and the standard deviation for all data points is only 14%.

C. Objective of the Present Work

After the study of literature discussed above, and others, which are not mentioned in this presentation due to their narrow field of

application, it is found that in general, none of the existing correlations appears to be entirely satisfactory for general use. However, Chen's correlation has been accepted as one of the best available under the flow conditions prescribed by him. A detail study of this correlation and modification for flow conditions other than prescirbed by Chen will be carried out in the present work. Shah's chart correlation appears to be considerably superior to any other available predictive technique. An attempt will be made to establish a functional relation for the heat transfer coefficient with different parameters used in his correlation.

CHAPTER III

Development of Correlation

It is seen from the literature survey in Chapter II that there are only two correlations which have had some success in predicting heat transfer coefficients under flow boiling conditions for a variety of liquids. These are Chen's correlation (Eqn. 2.5-9) and Shah's Chart correlation (Fig. 6). In this chapter these correlations are further investigated against the available experimental data from different sources and refinements are made to arrive at a correlation scheme for vertical and horizontal flow boiling conditions.

The correlation proposed by Chen has been accepted as one of the best available. It has been derived for the following flow conditions:

- i) saturated, two-phase fluid in convective flow
- ii) vertical, axial flow
- iii) stable flow
- iv) no slug flow
- v) no liquid deficiency
- vi) 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%.

Chen's correlation was originally developed for water and some organic fluids. However, Jallouk observed that Chen's correlation consistently underpredicted the heat transfer coefficient for the cases of refrigerants in vertical flow. A variable coefficient was proposed by Jallouk for the boiling part of heat transfer for different refrigerants.

An attempt is now made to apply and modify Chen's correlation for horizontal flow. Chawla's¹⁰ experimental data for R-11 is used as the basis of the correlation. A total of 181 data points are used in an iterative method described by Chen in his paper to obtain functional relationships among F , S , Re_{TP} and X_{tt} . The least square method for approximation of exponential constants has been tried using the Xerox Sigma 9 computer at RIT. The results obtained have been compared with the experimental values and have been found to be inconsistent. It is concluded that the tube orientation plays an important role probably through stratification effects and intermittent wetting and drying out of the top portion of the tube.

The Chart-correlation proposed by Shah appears to be considerably superior to any other available predictive technique. It takes into account the Boiling number, Convection number and the Froude number. However, this technique needs use of the chart for prediction of heat transfer coefficients after calculating the necessary parameters. The concept of additive contributions of convection and boiling heat transfer during flow boiling has been accepted by many investigators. However, Shah considers heat transfer coefficient to be a function of only Bo number (boiling contribution) in the nucleate boiling regime, and a

function of only Co number for low values of Co number corresponding to high vapor qualities or condition of pure convective boiling in which bubble nucleation has been assumed to be completely suppressed. The effect of both Bo and Co numbers is significant only in the transition region. A study of Shah's results, for the data analyzed by him, clearly indicates that his chart correlation underpredicts majority of the values. This leads to the concept of an additive mechanism to exist in all the regimes during flow boiling.

A. Vertical Flow:

In the present investigation convective as well as boiling contributions have been considered in all the regimes of flow boiling. Twenty-three (23) data points of Guerrieri and Talti² for upward flow of boiling cyclohexane in vertical tube and one hundred seven (107) data points of Wright¹¹ for downward flow of boiling water in vertical tube have been used in developing this correlation. The convective part during the flow boiling for the above data is well represented by the following correlation:

$$h_c = \begin{cases} \frac{0.533 h_{\ell}}{Co^{0.79}}, & \text{For } Co > 0.65 \\ \frac{1.876 h_{\ell}}{Co^{0.79}}, & \text{For } Co \leq 0.65 \end{cases} \quad (3.1)$$

where, h_c is two-phase heat transfer coefficient for convective contribution during flow boiling, and h_{ℓ} is the superficial heat transfer coefficient for liquid phase and is given by:

$$h_{\ell} = 0.023 \left[\frac{G(1-x)D}{\mu_{\ell}} \right]^{0.8} Pr_{\ell}^{0.4} \frac{k_{\ell}}{D} \quad (3.2)$$

For the boiling part of heat transfer during flow boiling, a trial-and-error method is used to arrive at the following correlation to yield a minimum RMS error with the experimental data of this study:

$$\begin{aligned} h_b &= 2.3 h_{\ell} (Bo \times 10^4)^{0.5}, \text{ for } Co > 0.65 \\ &= 0.7 h_{\ell} (Bo \times 10^4)^{0.9}, \text{ for } Co \leq 0.65 \end{aligned} \quad (3.3)$$

where h_b is boiling contribution to the two-phase heat transfer coefficient and h_{ℓ} is given by the Eq. (3.2).

The two-phase heat transfer coefficient, h_{TP} , is then obtained as the sum,

$$h_{TP} = h_c + h_b \quad (3.4)$$

The above equation in its final form for the case of vertical flow is given by:

$$h_{TP} = h_{\ell} \left[\frac{0.533}{Co^{0.79}} + 2.3 (Bo \times 10^4)^{0.5} \right], \text{ for } Co > 0.65 \quad (3.5)$$

and

$$h_{TP} = h_{\ell} \left[\frac{1.876}{Co^{0.79}} + 0.7 (Bo \times 10^4)^{0.9} \right], \text{ for } Co \leq 0.65 \quad (3.6)$$

where h_l is given by Eq. (3.2).

A comparison of the results obtained using the Eqs. (3.5) and (3.6) with Guerrieri and Talti's data are tabulated in Table 1. The mean deviation is 7.1%. The comparison of the correlation with the experimental data is shown in Fig. 7.

For eighty (80) data points of Wright, downward flow of water in vertical tube, test section 1, 0.7194" ID, the mean deviation is 18.4%. For the remaining twenty-seven (27) data points, test section 2, 0.4716" ID, the mean deviation is 19.7%. The results are tabulated in Tables 2 and 3 for the above test conditions. The comparison of the experimental data with the correlation (Eqs. 3.5 and 3.6) for both test sections is shown in Fig. 8.

As no other reliable data for flow boiling in vertical tubes was readily available, further testing of the correlation could not be carried out.

B. Horizontal Flow:

The flow patterns during generation of vapor in horizontal tubes are asymmetric (see Fig. 3), particularly at low inlet velocities. Intermittent drying and rewetting of the upper surfaces of the tube in wavy flow¹¹ and progressive drying out over long tube lengths of the upper circumference of the tube wall in annular flow have been observed

TABLE 1: DATA OF GUERRIERI AND TALTI²

Extracted from Fig. 6 of reference. Upward flow of boiling cyclohexane in vertical tubes. Pressure 15 psia. Local parameters.

G x 10 ⁻⁴	q	Bo x 10 ⁴	x	Co	h_{TP}/h_1		
					MEAS.	PRED.*	DEV.%
34.2	9,800	1.9	.0065	3.5	3.3	3.36	1.8
			.017	1.6	3.5	3.53	0.8
			.028	1.06	3.6	3.68	2.2
			.040	.79	4.0	3.81	-4.0
			.052	.63	4.2	3.95	-5.9
			.060	.56	4.3	4.21	-2.0
28.9	7,640	1.7	.013	1.98	3.6	3.31	-8.1
			.022	1.30	3.6	3.43	-4.7
			.035	.88	3.7	3.59	-2.9
			.042	.76	3.8	3.66	-3.6
			.055	.60	4.2	3.94	-6.2
			.061	.55	4.3	4.14	-3.7
35.6	2,500	.46	.0036	5.6	1.5	1.69	12.6
			.011	2.3	2.2	1.84	-16.0
			.018	1.5	2.3	1.95	-15.0
			.022	1.3	2.6	1.99	-23.0
			.025	1.16	2.7	2.03	-24.0
28.8	3,740	.84	.0065	3.5	2.2	2.30	4.5
			.012	2.1	2.4	2.40	0.0
			.018	1.5	2.5	2.49	-2.0
			.028	1.06	2.7	2.62	-2.9
			.032	.95	2.9	2.66	-8.1
			.035	.88	3.0	2.70	-10.0

* This Correlation.

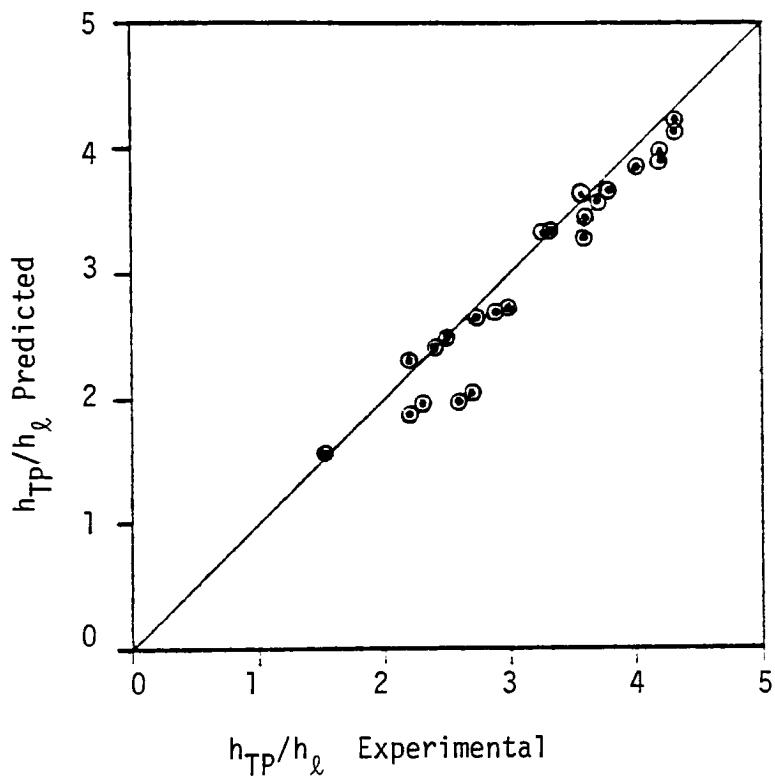


Fig. 7: Comparison of the correlation with the experimental data of Guerrieri and Talti².

TABLE 2: DATA OF WRIGHT¹¹

Downward flow of boiling water in vertical pipe. Test section 1, 0.7194" ID
 Local parameters

Test No.	W	$q \times 10^{-3}$	$Re_{13} \times 10^3$	$Bo_x \times 10^4$	p	x	Co	h_1	h_{TP}	h_{TP}/h_1		
										MEAS.	PRED*	% DEV.
41	1125	46.0	39.4	1.2	23.16	.0460	.34	826	5536	6.7	5.22	-22.0
					23.06	.0483	.32	825	4572	5.5	5.44	-1.1
					22.94	.0506	.31	822	4302	5.2	5.56	6.9
					22.70	.0552	.29	818	4322	5.3	5.81	9.7
					22.42	.0599	.27	814	4423	5.4	6.10	13.0
					22.09	.0647	.25	809	4506	5.6	6.43	14.9
					21.72	.0696	.24	804	4552	5.7	6.62	16.1
					21.29	.0747	.22	799	4541	5.7	7.03	23.3
					20.82	.0799	.21	793	4568	5.8	7.26	25.0
					20.28	.0853	.20	787	4792	6.1	7.51	23.2
					19.69	.0908	.18	781	5139	6.6	8.10	22.6
					19.07	.0965	.17	774	5694	7.4	8.43	13.9
					18.46	.1021	.16	767	8311	10.8	8.80	-18.5
58	1122	31.5	35.7	0.82	16.99	.0088	1.2	821	3234	3.9	2.54	-34.8
					16.99	.0102	1.0	820	2747	3.3	2.62	-20.6
					16.98	.0116	.94	819	2501	3.0	2.64	-12.0
					16.97	.0129	.87	818	2351	2.9	2.68	-7.0
					16.96	.0143	.80	817	2253	2.8	2.72	-2.8
					16.95	.0157	.74	816	2180	2.7	2.76	2.2
					16.93	.0172	.69	815	2147	2.6	2.79	7.0
					16.89	.0200	.61	812	2168	2.7	3.36	24.4
					16.84	.0229	.54	810	2228	2.7	3.64	34.7
					16.76	.0259	.49	808	2317	2.9	3.88	33.8
					16.66	.0290	.45	805	2456	3.0	4.11	37.0
					16.52	.0321	.41	802	2659	3.3	4.38	32.0
					16.37	.0353	.38	799	2973	3.7	4.61	24.7
16	1657	49.888	62.4	0.9	30.75	.0523	.35	1160	7174	6.2	4.94	-20.4
					30.54	.0542	.34	1157	6005	5.2	5.04	-3.1
					30.31	.0561	.33	1153	5544	4.8	5.14	7.1
					29.84	.060	.31	1147	5424	4.7	5.37	14.2
					29.31	.0641	.30	1140	5566	4.9	5.49	12.1
					28.72	.0682	.28	1132	5586	4.9	5.76	17.6
					28.05	.0725	.26	1125	5526	4.9	6.07	23.9
					27.40	.0769	.24	1118	5527	4.9	6.43	31.2
					26.68	.0813	.23	1110	5572	5.0	6.63	32.5
					25.90	.0859	.22	1103	5968	5.4	6.84	26.7
					25.00	.0908	.20	1094	6596	6.0	7.33	22.1
					23.96	.0960	.19	1083	7078	6.5	7.60	16.9
					22.82	.1015	.18	1072	7280	6.8	7.90	16.3

* This Correlation.

TABLE 2: DATA OF WRIGHT¹¹ (Continued)

Downward flow of boiling water in vertical pipe. Test section 1, 0.7194" ID
Local parameters

Test No.	W	$q \times 10^{-3}$	$Re_{13} \times 10^{-3}$	$Bo_x \times 10^4$	p	x	Co	h_1	h_{TP}	h_{TP}/h_1		
										MEAS.	PRED*	% DEV.
29	1646	31.66	62.0	.56	28.72	.0531	.34	1157	7444	6.4	4.81	-24.7
					28.46	.0546	.33	1155	6076	5.3	4.92	-7.2
					28.24	.0560	.32	1152	5527	4.8	5.03	4.8
					27.75	.0589	.31	1147	5438	4.7	5.14	9.5
					27.24	.0618	.30	1142	5481	4.8	5.27	9.8
					26.69	.0648	.28	1137	5441	4.8	5.54	15.5
					26.12	.0679	.27	1131	5361	4.7	5.69	21.0
					25.51	.0711	.26	1125	5253	4.7	5.85	-10.0
					24.86	.0744	.24	1119	5269	4.7	6.20	31.0
					24.15	.0778	.22	1112	5615	5.0	6.62	32.4
					23.39	.0814	.21	1104	6158	5.6	6.85	22.3
34	1126	31.468	39.6	.83	23.66	.0707	.24	812	5611	6.9	6.4	-7.2
					23.48	.0725	.23	810	5035	6.2	6.6	6.5
					23.29	.0743	.23	808	4744	5.9	6.6	11.8
					22.9	.0780	.22	804	4670	5.8	6.8	17.2
					22.49	.0817	.21	800	4710	5.9	7.0	18.6
					22.05	.0855	.20	795	4735	5.9	7.3	23.7
					21.57	.0894	.19	791	4699	5.9	7.5	27.1
					21.08	.0933	.18	786	4634	5.9	7.8	32.2
					20.58	.0973	.18	781	4628	5.9	7.8	32.2
					20.01	.1015	.17	776	4776	6.2	8.2	32.2
					19.44	.1057	.16	770	5228	6.8	8.6	26.4
121	904	46.028	31.1	1.50	21.83	.0583	.28	682	6147	9.0	6.1	-32.2
					21.78	.0594	.27	681	4814	7.1	6.3	-11.2
					21.72	.0610	.27	680	3733	5.5	6.3	14.5
					21.60	.0638	.26	678	3785	5.6	6.4	14.3
					21.48	.0666	.25	676	3850	5.7	6.6	15.8
					21.35	.0694	.24	674	3918	5.8	6.8	14.7
					21.07	.0752	.22	670	4053	6.0	7.2	20.0
					20.76	.0810	.21	665	4181	6.3	7.4	17.5
					20.39	.0869	.19	660	4310	6.5	7.9	21.5
					19.98	.0929	.18	655	4465	6.8	8.3	22.0
					19.50	.0991	.17	650	4601	7.1	8.6	21.1
					19.03	.1045	.16	644	4735	7.3	8.9	21.9
17.93	1182	.1117	.15	1.50	18.50	.1117	.15	639	4932	7.7	9.4	22.0
					17.93	.1182	.14	633	5224	8.3	9.9	19.2
17.34	1248	.1248	.13	1.50	17.34	.1248	.13	626	6010	9.6	10.4	8.3

* This Correlation.

TABLE 3: DATA OF WRIGHT¹¹

Downward flow of boiling water in vertical pipe. Test section 2, ID 0.4716 in.
Local parameters

Test No.	W	$q_x \cdot 10^{-3}$	$Re_{1x} \cdot 10^{-3}$	$Bo_x \cdot 10^4$	p	x	Co	h_1	h_{TP}	h_{TP}/h_1		
										MEAS.	PRED*	% DEV.
159	1055	88.009	60.1	1.07	29.52	.0014	6.7	1717	3551	2.1	2.5	19.0
					29.47	.0014	6.7	1712	3299	1.9	2.5	31.5
					29.37	.0043	2.7	1707	3301	1.9	2.6	36.8
					28.12	.0232	.68	1672	3955	2.4	2.9	20.8
					27.27	.0305	.55	1656	5565	3.4	3.8	11.7
					26.12	.0384	.43	1638	6182	3.8	4.4	15.8
					24.47	.0474	.35	1614	6653	4.1	5.0	21.9
					23.43	.0525	.31	1599	7164	4.5	5.5	22.2
					22.02	.0585	.28	1580	9191	5.8	5.9	1.7
					20.85	.0630	.26	1564	13633	8.7	6.2	-28.7
58	1122	31.5	35.7	0.82	54.67	.0009	12.8	3282	5166	1.6	1.7	6.3
					54.62	.0015	8.5	3280	4529	1.4	1.7	21.4
					54.55	.0024	5.8	3277	4486	1.4	1.8	28.5
					54.41	.0039	4.0	3272	4448	1.4	1.8	28.5
					49.13	.0243	.84	3179	6054	1.9	2.3	21.1
					46.94	.030	.69	3150	7060	2.2	2.4	9.1
					44.17	.0366	.60	3116	8038	2.6	3.2	23.1
					42.38	.0406	.51	3093	8746	2.8	3.6	28.5
					39.85	.0458	.45	3057	10231	3.3	3.9	18.2
					37.35	.0505	.41	3018	14084	4.7	4.2	-10.6
16	1657	49.888	62.7	0.9	25.67	.0464	.36	1027	6385	6.2	4.8	-22.5
					25.57	.0475	.35	1026	5071	4.9	4.9	0.0
					25.42	.0490	.34	1024	4489	4.4	4.9	11.4
					25.13	.0517	.33	1020	4263	4.2	5.1	21.4
					24.86	.0544	.31	1017	4314	4.2	5.3	26.2
					24.57	.0571	.30	1013	4344	4.3	5.4	25.6
					17.07	.1044	.15	932	6700	7.2	8.9	23.6

* This Correlation.

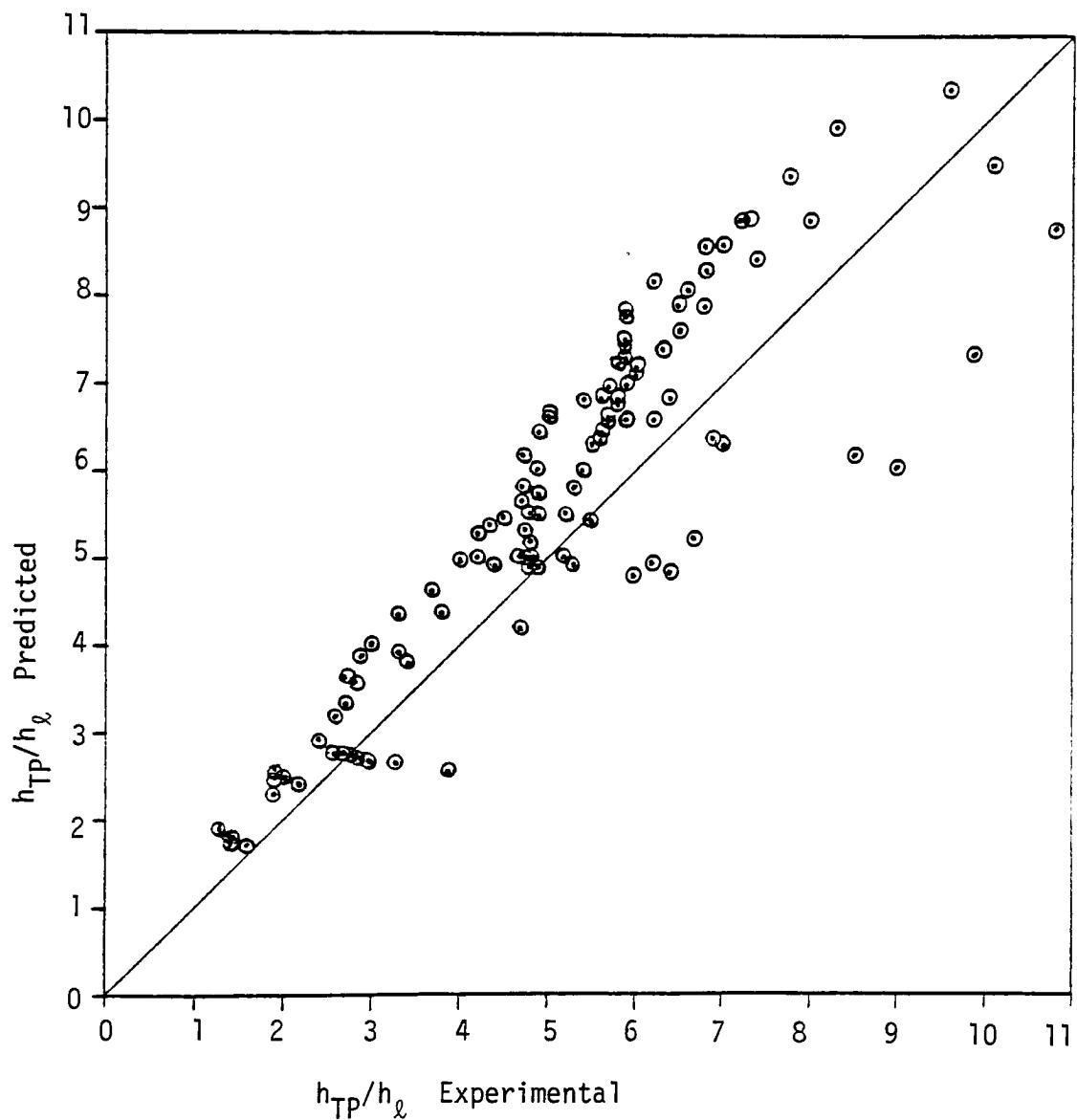


Fig. 8: Comparison of the correlation with the experimental data of Wright¹¹.

during testing by many researchers. However, at higher inlet liquid velocities, the influence of gravity is less pronounced, the phase distribution becomes more symmetrical, and flow patterns resemble to those seen in vertical upward flow

A study of experimental data analyzed during this investigation (see data of Mumm¹² Tables 4-7) revealed that tube orientation does not affect the heat transfer rate at very low quality of vapor (corresponding to high Co number). This may be due to the fact that the tube walls are fully wet at such low qualities. This is true for Co numbers up to 0.65. Eq. (3.5) yields satisfactory results for horizontal flow with Co number greater than 0.65. However, when the tube walls are not completely wet and a dry-out situation occurs, the heat transfer rate drops. The heat transfer coefficients for partially dry surfaces are lower than completely wet surfaces. The greater the portion of surface remaining dry, the lower would be the heat transfer rate.

Based on the above findings, a correction factor is needed to represent the fraction of the tube circumference that remains dry. The Froude number has been established to be the controlling factor in wave formation in stratified flow. High values of Froude number will ensure wave formation and absence of stratified flows. Also, the inertia force tends to cause film climbing, resisted by surface tension and gravitational forces. Surface tension forces are generally negligible in comparison to gravitational and inertia forces. For any particular fluid the ratio of gravitational forces to inertia forces would then determine the film climbing and tube surface wetting. Froude number is that ratio.

By a trial-and-error method, it is found that a correction factor of $(25 \times \text{Froude number})^{0.24}$ to the Eq (3.6) gives satisfactory results for horizontal flow, for Froude number less than 0.04. No correction factor is needed for Froude number greater than 0.04. However, during testing of above correction factor with Chawla¹⁰ data (181 data points considered) for R-11 boiling in horizontal tubes, an interesting fact has been observed. The mean error has been found to be minimum by using different correction factors for the convective and the boiling parts of the Eq. (3.6), leading to the fact that the convective and the boiling parts of the heat transfer during flow boiling are not affected equally in case of horizontal flow.

Finally, the correlation suggested on the basis of above evaluation, for the heat transfer coefficient during flow boiling in case of horizontal flow is

For $Co > 0.65$,

$$h_{TP} = h_\ell \left[\frac{0.533}{Co^{0.79}} + 2.3 (Bo \times 10^4)^{0.5} \right] \quad (3.7)$$

and for $Co \leq 0.65$,

$$\begin{aligned} h_{TP} &= h_\ell \left[\frac{1.876}{Co^{0.79}} + 0.7 (Bo \times 10^4)^{0.9} \right], \text{ For } Fr_\ell \geq 0.04 \\ &= h_\ell \left[1.876 \left(\frac{1}{Co} \right)^{0.79} \times (25 \times Fr_\ell)^{0.3} \right. \\ &\quad \left. + 0.7 (Bo \times 10^4)^{0.9} \times (25 \times Fr_\ell)^{0.1} \right], \text{ for } Fr_\ell < 0.04 \end{aligned} \quad (3.8)$$

where, Fr_l is the Froude number assuming all mass flowing in liquid form and is given by:

$$Fr_l = \frac{V^2}{gD} \quad (3.9)$$

The results obtained using Eq. (3.7) and (3.8) for 181 data points of Chawla for R 11 boiling in horizontal tubes are as follows:

- i) Mean deviation 16.1% - for saturation temperature 32°F and tube ID 25mm (51 data points).
- ii) Mean derivation 13.0% - for saturation temperature 68°F and tube ID 25mm (33 data points).
- iii) Mean deviation 13.6% - for saturation temperature 50°F and tube ID 14mm (31 data points).
- iv) Mean deviation 16.3% - for saturation temperature 50°F and tube ID 6mm (66 data points.)

The overall mean deviation of the result obtained considering all 181 data points is 15.1%. The comparison of the correlation with the experimental data is shown in Fig. 9. The computer program and the results obtained are given in Appendix A.

The correlation has also been tested with the experimental data of Mummm¹² for boiling water in horizontal tube for different test conditions. A total of 189 data points have been considered. The results obtained are given below:

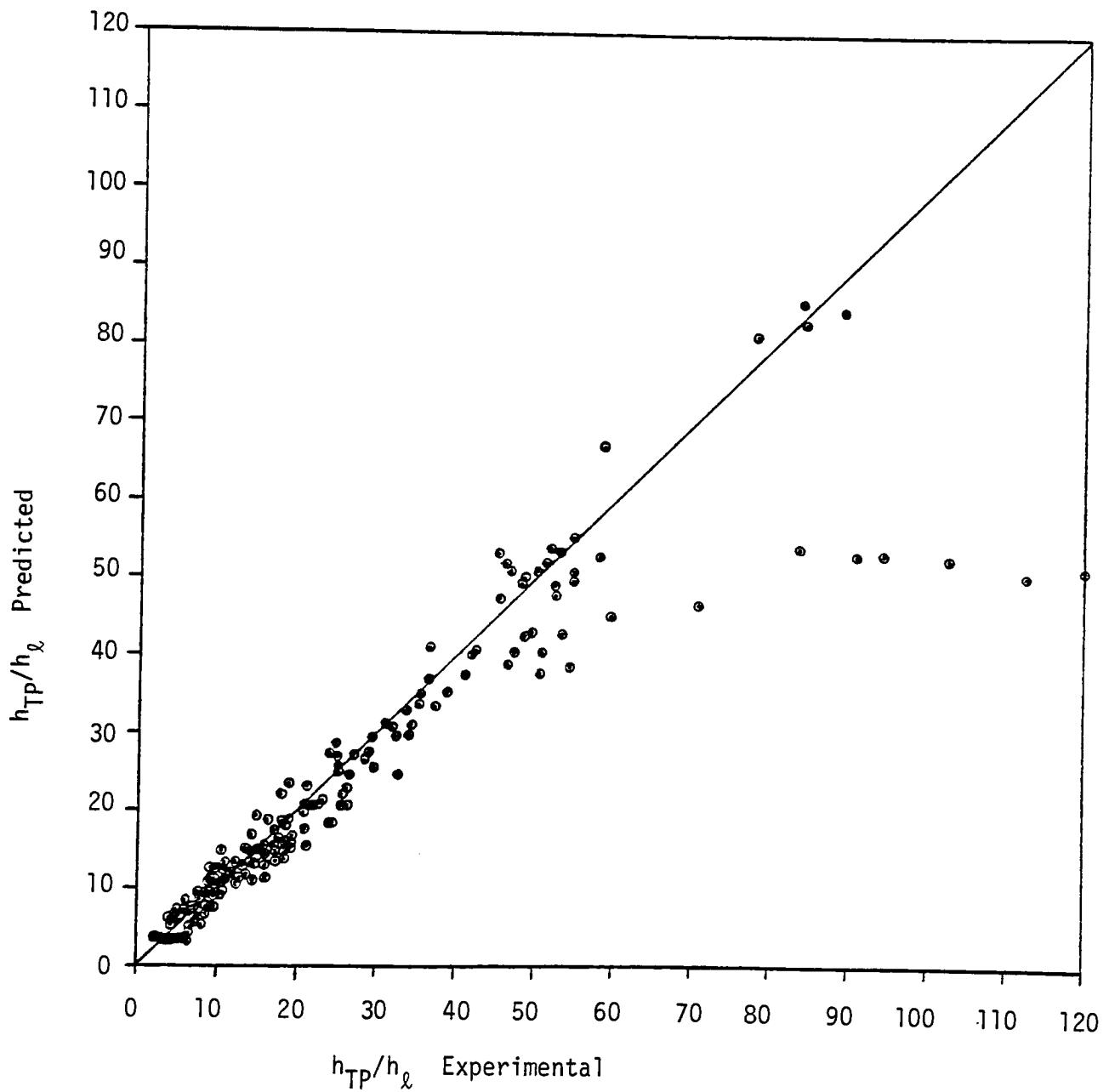


Fig. 9: Comparison of the correlation with the experimental data of Chawla¹⁰.

- i) Mean deviation 9.9% - tube ID 0.465", saturation pressure
45 psia (94 data points).
- ii) Mean deviation 10.8% - tube ID 0.465" saturation pressure
90 psia (56 data points).
- iii) Mean deviation 6.9% - tube ID 0.465", saturation pressure
150 psia (20 data points).
- iv) Mean deviation 9.3% - tube ID 0.465" saturation pressure
200 psia (19 data points).

The overall mean deviation considering all 189 points is 9.8%. The results obtained for the above test conditions along with local parameters are tabulated in Tables 4-7. The comparison of the correlation with the experimental data is shown in Fig. 10.

The correlation obtained for predicting the two-phase heat transfer coefficients for the test conditions analyzed in this chapter for vertical flow is given by the Eqs. (3.5)and (3.6) and by Eqs. (3.7) and (3.8)for horizontal flow.

TABLE 4: DATA OF MUMM¹²

Horizontal pipe 0.465 in. ID. Boiling water at 45 psia. Local parameters.

Test No.	$G \times 10^{-6}$	$q \times 10^{-6}$	$Re_1 \times 10^{-3}$	Fr_1	$Bo \times 10^4$	x	Co	h_1	h_{TP}	h_{TP}/h_1		
										MEAS.	PRED*	% DEV.
75	1.02	0.05	82.3	19.0	0.53	0	--	2190	4590	2.1	1.7	-19.0
						.005	3.03	2190	4800	2.2	1.9	-13.6
						.01	1.73	2170	5150	2.4	2.1	-12.5
						.02	.98	2155	6250	2.9	2.4	-17.2
76	1.02	0.1	82.3	19.0	1.06	0	--	2190	4350	2.0	2.3	15.0
						.01	1.73	2170	5450	2.5	2.6	4.0
						.02	.98	2155	6600	3.1	2.8	-9.0
						.0375	.59	2124	8900	4.2	3.6	-10.0
77	1.02	0.15	82.3	19.0	1.58	0	--	2190	5420	2.5	2.8	12.0
						.01	1.73	2170	6150	2.8	3.1	10.7
						.02	.98	2155	6960	3.2	4.0	25.0
						.04	.56	2120	9150	4.3	4.8	11.6
						.058	.41	2088	10200	4.9	4.9	0.0
78	1.02	.20	82.3	19.0	2.1	0	--	2190	6400	2.9	3.3	13.7
						.01	1.73	2170	6920	3.2	3.6	12.5
						.03	.703	2137	8750	4.1	4.0	-2.0
						.05	.46	2102	10200	4.8	4.8	0.0
						.077	.32	2054	10600	5.2	5.9	13.4
79	1.02	.25	82.3	19.0	2.6	0	--	2190	7450	3.4	3.7	9.0
						.01	1.73	2170	7940	3.7	4.0	8.1
						.03	.70	2137	9250	4.3	4.4	2.3
						.06	.40	2084	10800	5.2	5.5	5.7
						.094	.27	2024	10800	5.3	6.9	30.0
137	.255	.150	20.57	1.19	6.3	0	--	722	3614	5.0	5.7	14.0
						.04	.56	699	3856	5.5	5.5	0.0
						.08	.31	675	4702	7.0	8.4	20.0
						.12	.22	635	6302	9.9	9.9	0.0
						.15	.18	614	7177	11.7	10.9	-6.8
						.20	.13	603	7853	13.0	13.0	0.0
						.24	.11	580	8721	15.0	14.4	-4.0
						.28	.093	555	9036	16.3	15.9	-2.4
						.323	.080	528	9434	17.9	17.5	-2.2
65B	.382	.250	30.82	2.66	7.05	0	--	997	5952	6.0	6.1	1.7
						.05	.46	951	6720	7.0	7.5	7.1
						.10	.25	916	7575	8.3	9.6	15.6
						.15	.18	875	8446	9.6	11.3	17.7
						.20	.13	834	9434	11.3	13.4	18.5
						.25	.10	792	10729	13.5	15.6	15.5
						.284	.090	763	11111	14.6	16.6	13.7

* This Correlation.

TABLE 4: DATA OF MUMM¹² (Continued)

Horizontal pipe 0.465 in. ID. Boiling water at 45 psia. Local parameters.

h_{TP}/h_1

Test No.	$G \times 10^{-6}$	$q \times 10^{-6}$	$Re \times 10^{-3} \times$	Fr_1	$Bo \times 10^4$	x	Co	h_1	h_{TP}	h_{TP}/h_1		
										MEAS.	PRED*	% DEV.
69	.382	.050	30.82	2.66	1.4	0	--	997	3205	3.2	2.7	-15.6
						,02	.96	981	3521	3.6	3.3	-8.3
						.04	.54	965	4032	4.2	4.0	-4.7
						.058	.39	950	4310	4.5	4.9	8.8
68	.382	.100	30.82	2.66	2.8	0	--	997	3448	3.5	3.8	8.5
						.03	.68	972	4000	4.1	4.5	9.7
						.06	.38	945	4762	5.0	5.8	16.0
						.09	.27	924	5555	6.0	7.0	17.4
						.113	.22	905	6622	7.3	7.9	8.2
67	.382	.150	30.82	2.66	4.2	0	--	997	4573	4.8	4.7	-2.0
						.04	.54	965	5300	5.5	5.6	1.8
						.08	.30	933	5905	6.3	7.4	17.5
						.12	.21	900	6726	7.5	8.9	18.6
						.16	.16	867	7575	8.7	10.5	20.6
						.172	.15	857	7895	9.2	10.9	18.5
135	0.250	0.250	20.17	1.14	10.8	0	--	711	5543	7.8	7.6	-2.5
						.05	.45	682	5981	8.8	9.5	7.9
						.10	.25	653	6510	10.0	11.5	15.0
						.15	.17	624	7122	11.4	13.5	18.4
						.20	.13	595	7988	13.4	15.3	14.1
						.25	.10	565	8680	15.4	17.5	13.6
						.30	.087	534	9363	17.5	18.8	7.4
						.35	.072	504	10040	19.9	20.9	5.0
						.40	.060	472	10869	23.0	23.3	1.3
						.45	.051	441	12019	27.2	25.7	-5.5
						.47	.048	428	11848	27.7	26.6	-3.9
						.48	.046	421	11574	27.5	27.3	-0.7
						.504	.042	406	10246	25.2	28.9	14.6
						.52	.040	395	8960	22.7	29.8	31.2
136	.250	.200	20.17	1.14	8.6	0	--	711	4444	6.2	6.7	8.0
						.05	.45	682	4819	7.1	8.4	18.3
						.10	.25	653	5934	9.1	10.4	14.2
						.15	.17	624	7490	12.0	12.4	3.3
						.20	.13	595	8510	14.3	14.3	0.0
						.25	.10	565	9302	16.5	16.4	-0.6
						.30	.087	534	10100	18.9	17.8	-5.8
						.35	.072	504	10256	20.3	19.9	-1.9
						.40	.060	472	11428	24.2	22.2	-8.2
						.41	.057	466	11627	24.9	22.9	-8.0
						.42	.055	460	10638	23.1	23.4	1.3
						.432	.052	452	8888	19.7	24.2	22.8

* This Correlation.

TABLE 4: DATA OF MUMM¹² (Continued)

Horizontal pipe 0.465 in. ID. Boiling water at 45 psia. Local parameters.

Test No.	$G \times 10^{-6}$	$q \times 10^{-6}$	$Re_1 \times 10^{-3}$	Fr_1	$Bo \times 10^4$	x	Co	h_1	h_{TP}	h_{TP}/h_1		
										MEAS.	PRED.*	% DEV.
74	.765	.076	61.7	10.67	1.08	0.	--	1741	5800	3.3	2.4	-27.2
						.01	1.7	1727	6650	3.8	2.8	-26.3
						.02	.98	1713	7650	4.5	2.93	-34.3
73	.765	.050	61.7	10.67	0.7	.0295	.72	1700	5550	3.3	3.1	-6.0
						0	--	1741	4350	2.5	2.7	8.0
						.01	1.7	1727	4750	2.7	3.0	11.1
						.02	.98	1713	5250	3.1	3.2	3.2
72	.765	.151	61.7	10.67	2.1	0	--	1741	5150	3.0	3.3	10.0
						.02	.98	1713	6016	3.5	3.8	8.5
						.04	.56	1685	7475	4.4	4.3	-2.2
						.06	.40	1657	8531	5.1	5.2	1.9
						.08	.31	1629	9681	5.9	6.1	3.3

* This Correlation.

TABLE 5: DATA OF MUMM¹²

Boiling water in horizontal pipe 0.465 in. ID. Saturation pressure 90 psia.
Local parameters.

Test No.	$G \times 10^{-6}$	$q \times 10^{-6}$	$Re_{13} \times 10^{-3}$	Fr_1	$Bo \times 10^4$	x	Co	h_1	h_{TP}	h_{TP}/h_1		
										MEAS.	PRED.*	% DEV
99	.382	.050	36.9	2.8	1.46	0	--	1080	3472	3.2	2.8	-12.5
						.02	1.37	1062	3597	3.4	3.2	-5.8
						.04	.77	1045	3731	3.6	3.5	-2.7
						.063	.52	1025	3875	3.8	4.1	7.9
98	.382	.100	36.9	2.8	2.92	0	--	1080	4504	4.2	3.9	-7.1
						.03	.97	1054	4504	4.3	4.4	2.3
						.06	.54	1027	4950	4.8	4.9	2.0
						.09	.38	1001	5780	5.8	5.8	0.0
						.118	.30	977	6944	7.1	6.7	-5.6
97	.382	.150	36.9	2.8	4.4	0	--	1080	5725	5.3	4.8	-9.4
						.04	.77	1045	6000	5.7	5.5	-3.5
						.08	.43	1010	6410	6.3	6.3	0.0
						.12	.30	975	6726	6.9	7.5	8.6
						.179	.20	922	7142	7.7	9.3	20.7
96	.382	.20	36.9	2.8	5.85	0	--	1080	6896	6.4	5.6	-12.5
						.06	.54	1027	7353	7.2	6.5	-9.7
						.12	.30	975	7782	8.0	8.2	2.5
						.18	.20	922	8197	8.9	10.1	13.4
						.239	.15	868	8620	9.9	11.8	19.1
84	1.02	.05	98.56	19.9	0.55	0	--	2370	4587	1.9	1.7	-10.5
						.01	2.4	2351	5050	2.1	2.0	-4.7
						.02	1.35	2332	5617	2.4	2.1	-12.5
						.023	1.2	2326	5682	2.4	2.2	-8.3
83	1.02	.10	98.56	19.9	1.09	0	--	2370	6250	2.6	2.4	-7.6
						.01	2.4	2351	6757	2.9	2.7	-6.8
						.02	1.35	2332	7812	3.3	2.8	-15.0
						.03	.95	2313	8474	3.7	3.0	-21.0
						.043	.71	2288	8772	3.8	3.1	-18.4
82	1.02	.150	98.56	19.9	1.64	0	--	2370	7500	3.2	2.9	-7.9
						.02	1.35	2332	8474	3.6	3.4	-5.5
						.04	.76	2294	8982	3.9	3.6	-7.5
						.064	.51	2248	9091	4.0	4.3	7.5
81	1.02	.200	98.56	19.9	2.19	0	--	2370	8810	3.7	3.4	-8.0
						.01	2.4	2351	9216	3.9	3.7	-5.1
						.03	.97	2313	10000	4.3	4.0	-7.0
						.05	.63	2275	10638	4.7	4.1	-12.7
						.085	.40	2207	11364	5.1	5.3	3.9

* This Correlation.

TABLE 5 : DATA OF MUMM¹² (Continued)

Boiling water in horizontal pipe 0.465 in. ID. Saturation pressure 90 psia.
Local parameters.

Test No.	$G \frac{x}{10^{-6}}$	$q \frac{x}{10^{-6}}$	$Re_1 \frac{x}{10^{-3}}$	Fr_1	$Bo \frac{x}{10^4}$	x	Co	h_1	h_{Tp}	$\frac{h_{Tp}}{h_1}$		
										MEAS.	PRED.*	% DEV.
140	.255	.250	24.64	1.24	10.95	0	--	782	5330	6.8	7.6	11.8
						.03	.97	763	5568	7.3	8.1	10.9
						.06	.54	744	6112	8.2	9.1	10.9
						.09	.38	725	7267	10.0	10.0	0.0
						.12	.30	706	9294	13.2	10.9	-17.4
						.15	.24	687	11848	17.2	11.8	-31.2
						.20	.18	654	12438	19.0	13.3	-29.9
						.30	.12	588	12500	21.2	16.1	-24.1
						.40	.084	520	12820	24.6	19.3	-21.5
						.50	.060	449	12820	28.5	23.4	-17.9
						.53	.054	427	12886	30.2	24.9	-17.5
						.55	.051	413	11574	28.0	25.7	-8.1
						.563	.049	403	10160	25.2	26.4	4.7
95	.382	.250	36.9	2.8	7.3	0	--	1080	7837	7.3	6.2	-15.1
						.06	.54	1027	8170	7.9	7.2	-8.3
						.12	.30	975	8591	8.8	9.0	2.2
						.18	.20	921	8741	9.5	10.9	14.7
						.24	.15	869	8928	10.3	12.6	22.3
						.298	.12	814	9191	11.3	14.2	25.7

* This Correlation.

TABLE 6: DATA OF MUJMM¹²

Boiling water in horizontal pipe 0.465 in. ID. Saturation pressure 150 psia.
Local parameters.

Test No.	$G x \times 10^{-6}$	$q x \times 10^{-6}$	$Re_1 x \times 10^{-3}$	Fr_1	$Bo x \times 10^4$	x	Co	h_1	h_{TP}	h_{TP}/h_1		
										MEAS.	PRED.*	% DEV.
127	.510	.150	56.46	5.26	3.4	0	--	1439	5790	4.0	4.2	5.0
						.03	1.25	1404	6302	4.5	4.6	2.2
						.06	.70	1368	6849	5.6	4.9	-12.5
						.09	.49	1334	7692	5.8	5.4	-6.8
						.12	.38	1299	8474	6.5	6.1	-6.1
						.141	.33	1274	9554	7.5	6.6	-12.0
126	.510	.20	56.46	5.26	4.5	0	--	1439	6410	4.5	4.9	8.0
						.03	1.25	1404	6920	4.9	5.3	8.1
						.06	.70	1368	7407	5.4	5.6	3.7
						.09	.49	1334	7968	6.0	6.0	0.0
						.12	.33	1299	8733	6.7	7.2	7.4
						.15	.31	1263	9662	7.6	7.4	-2.1
						.184	.25	1223	10526	8.6	8.3	-3.5
125	.510	.25	56.46	5.26	5.7	0	--	1439	8741	6.1	5.5	-9.8
						.04	.98	1393	9225	6.6	6.0	-10.0
						.08	.55	1346	9765	7.2	6.4	-11.1
						.12	.38	1299	10593	8.1	7.4	-8.6
						.16	.29	1252	11312	9.0	8.3	-7.7
						.20	.23	1204	12136	10.1	9.3	-7.9
						.228	.20	1170	12500	10.7	10.0	-7.0

* This Correlation.

TABLE 7 : DATA OF MUMM¹²

Boiling water in horizontal pipe 0.465 in. ID. Saturation pressure 200 psia.
Local parameters.

Test No.	$G \times 10^{-6}$	$q \times 10^{-6}$	$Re_{13} \times 10^{-3}$	Fr_1	$Bo \times 10^4$	x	Co	h_1	h_{TP}	h_{TP}/h_1		
										MEAS.	PRED.*	% DEV.
132	.382	.150	44.6	2.9	4.6	0	--	1198	6329	5.3	4.9	-7.0
						.04	1.1	1159	6550	5.6	5.4	-3.6
						.08	.61	1120	6757	6.0	5.5	-8.3
						.12	.42	1081	7075	6.5	6.5	0.0
						.16	.33	1042	7109	6.8	7.2	5.8
						.194	.27	1008	7246	7.2	8.0	11.1
130	.382	.250	44.6	2.9	7.7	0	--	1198	8361	7.0	6.4	-8.6
						.05	.90	1150	8305	7.2	7.0	-2.7
						.10	.50	1101	8474	7.7	7.6	-1.3
						.15	.34	1052	8444	8.0	8.8	10.0
						.20	.26	1002	8446	8.4	9.8	16.6
						.25	.20	951	8834	9.3	11.1	19.4
						.318	.15	882	8834	10.0	12.8	28.0
131	.382	.200	44.6	2.9	6.2	0	--	1198	6969	5.8	5.7	-1.7
						.05	.91	1150	7168	6.2	6.3	1.6
						.10	.50	1101	7407	6.7	6.8	1.5
						.15	.34	1052	7663	7.3	8.0	9.6
						.20	.26	1002	7752	7.7	9.0	20.0
						.255	.20	947	8097	8.5	10.3	21.2

* This Correlation.

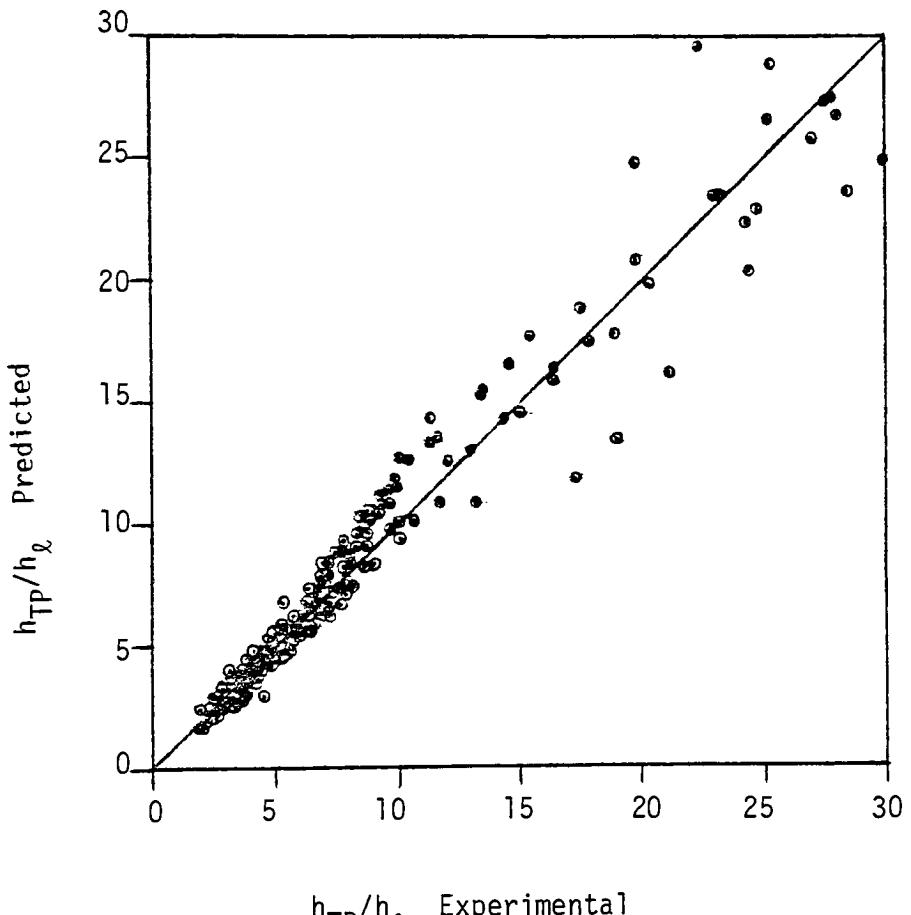


Fig. 10: Comparison of the correlation with the experimental data of Mumm¹².

CHAPTER IV
RESULTS AND DISCUSSION

A. Testing of the correlation with other data:

In Chapter III, the data of Guerrieri and Talti for cyclohexane and the data of Wright for water have been used for developing the proposed correlation (Eqs. 3.5 and 3.6) for flow boiling in vertical tubes. The correlation has been modified for the case of horizontal flow and has been tested with the data of Chawla for R-11 and the data of Mumm for water. In this chapter the correlation is further tested with other available experimental data.

i) Vertical Flow:

Jallouk carried out an extensive study of two-phase flow characteristics of refrigerants in vertical tubes. He measured the heat transfer coefficients for R-114 boiling in a 0.785" ID, 10' long vertical tube. The boiling temperature was varied from 100-200°F. The mass flux range was $0.12-3.5 \times 10^6 \text{ lbm/hr-ft}^2$. Forty-five (45) data points have been taken from Jallouk's experimental data and the heat transfer coefficients have been calculated using Eqs. (3.5) and (3.6). The results have been found to underpredict consistently the experimental values (44% mean error). Jallouk observed similar deviations with Chen's correlation and suggested a modified constant of 0.3802 to be used in place of 0.172 in Foster and Zuber's nucleate boiling correlation for the boiling part of heat transfer (see Eq. 2.10). By using the same modification factor for the boiling part of this correlation (Eqs. 3.5 and 3.6), a satisfactory result has been obtained. The modified correlation for R-114

boiling in vertical tube is given below:

$$h_{TP} = h_\lambda \frac{0.533}{Co^{0.79}} + 5.08(Bo \times 10^4)^{0.5}, \text{ For } Co > 0.65 \quad (4.1)$$

$$h_{TP} = h_\lambda \frac{1.876}{Co^{0.79}} + 1.547(Bo \times 10^4)^{0.9}, \text{ For } Co \leq 0.65 \quad (4.2)$$

The mean deviation for the data of Jallouk for R-114 is 16.7%, using the Eqs. (4.1) and (4.2). The computer program and the results obtained are given in Appendix B.

As no other reliable data for flow boiling in vertical tubes could be obtained, further testing of the correlation could not be carried out.

ii) Horizontal Flow:

Gouse and Coumou¹³ measured heat transfer coefficients during flow of R-113 in a horizontal glass tube which was heated by passing electric current through a transparent coating applied to the outer surface of the tube. Ten (10) data points have been used for testing the proposed correlation. The test conditions and the results using Eqs. (3.7) and (3.8) are given in Table 8. The mean deviation from the measured values of heat transfer coefficients is 5.1%.

TABLE 8: DATA OF GOUSE AND COUMOU¹³

Extracted from Fig. 4 and 6 of reference. Boiling R-113 in a horizontal glass tube 0.43 in. ID. Local parameters.

Test No.	W	q	Re_1	Fr_1	Bo	T	x	Co	h_1	h_{TP}	h_{TP}/h_1		
			$\times 10^{-3}$	$\times 10^3$	$\times 10^4$						MEAS.	PRED.*	DEV.%
6	520	4,100	15.28	2050	1.28	122	.0228	1.44	106	300	2.8	3.0	7.1
						121	.0471	.79	104	360	3.5	3.2	-8.6
						120	.0748	.53	102	405	4.0	4.0	0.0
						119	.106	.39	99	450	4.5	4.8	6.7
14	385	7,000	11.90	1123	2.96	130	.032	1.2	87.6	350	4.0	4.4	10.0
						130	.087	.51	83.6	405	4.8	5.0	4.1
						129	.159	.30	78.3	500	6.4	6.7	4.7
						126	.219	.21	74.4	595	8.0	8.3	3.8
						122	.288	.15	64.9	630	9.7	10.3	6.2
						117	.366	.11	59.1	750	12.6	12.6	0.0

* This Correlation.

B. Comparison of Results With Other Correlations:

i) Vertical Flow:

The experimental data used for the development and testing of this correlation have been compared with the results of other correlations discussed in Chapter II. The ranges of conditions for data used are given in Tables 9 and 10, the comparison of correlations are shown in Table 10.

Chen has not considered data points with less than 2% quality for Guerrieri and Talti's data and less than 1% quality for Wright's data. The number of data points analyzed by Chen is not known.

For the case of R-114 (Jallouk's data, vertical tube), Chen's correlation has underpredicted consistently 0 to -50%, as reported by Jallouk. The deviations are even higher using Shah's chart correlation (Fig. 6). The present correlation has also given similar results, however using the modified correlation, Eqs. (4.1) and (4.2), the mean deviation is reduced to 16.7%.

ii) Horizontal Flow:

For the case of horizontal flow, a general correlation is not available, except Shah's chart correlation. The ranges of conditions for the data used in testing the correlation are given in Table 11. Table 12 shows a comparison with the results of Shah's chart correlation

Table 9: Range of conditions for data used in developing this correlation, vertical flow.

Data	Fluid	Flow	Pressure psia	Flow Vel. ft/sec.	Quality liq. Wt. %	$Q/A \times 10^{-4}$ Btu/hr-ft ²
Guerrieri and Talti	cyclo- hexane	upward	15	1.3-2.8	0.65-6.1	0.3-1.3
Wright	water	downward	16-55	1.8-11.2	0.8-12	1.3-8.8

Table 10: Comparison of Correlations, vertical flow.

Data	Mean % Deviation						This Correlation
	Dengler and Addams	Guerrieri and Talti	Bennet et al	Schrock and Grossman	Chen	Shah	
Guerrieri and Talti (Cyclo- hexane)	39.8	11.1	65.9	50.7	13.6	16.3	7.3
Wright (water)	24.0	75.8	30.4	51.7	15.4	13.4	18.7

Number of data points considered = 130

Mean deviation for all data this correlation: giving equal weight to
each set of data = 13.0%
giving equal weight to
each data point = 16.6%

Table 11: Range of conditions for data used in testing this correlation, horizontal flow.

Data	Fluid	Flow	Saturation Temp. °F	$G \times 10^{-6}$ lb./hr.ft ²	$Q/A \times 10^{-6}$	Quality Wt. %
Chawla	R-11	horizontal	32-68	0.009-0.184	0.0004-0.022	10-98
Mumm	Water	horizontal	275-382	0.25-1.02	0.05-0.25	0-54
Gouse and Coumou	R-113	horizontal	117-130	0.38-0.51	0.004-0.007	2-37

Table 12: Comparison of Correlations, horizontal flow.

Data	Fluid	Test Condition	Mean % Deviation	
			Shah	This Correlation
Chawla	R-11	25mm ID	16.0	14.8
		14mm ID	10.3	13.6
		6 mm ID	28.5	16.3
Mumm	Water	0.465" ID	12.8	9.8
Gouse and Coumou	R-113	0.43" ID	10.7	5.1

Number of data points considered = 380

Mean deviation for all data this correlation: giving equal weight to each set of data = 10.0% giving equal weight to each data point = 12.2%

CHAPTER V
CONCLUSIONS AND RECOMMENDATIONS

The proposed correlation for vertical flow (Eqs. 3.5 and 3.6) has shown an excellent agreement with the data of Guerrieri and Talti (cyclohexane). For the data of Wright (water), the deviations are comparatively higher. Wright conducted his experiments by generating the vapor quality outside the test section, preheating the water to near the saturation temperature and then flashing it by throttling through a valve. Wright himself eliminated all data in the entrance regions, which he had defined as the length in which the heat transfer coefficients decrease with increasing vapor quality. He had also eliminated those data near the exit section with abnormally high heat transfer coefficients. Chen also used the same criteria for data selection in developing his correlation. Furthermore, Wright's analysis shows that his reported heat transfer coefficients may be seriously in error for low wall superheats. For this reason, data for boiling number less than 0.5×10^{-4} have not been considered during development of this correlation. The results of the present investigation would be significantly improved if the data points were selected according to the procedure used by Wright.

In the case of Jallouk's data for R-114 (vertical flow), all the correlations have given large deviations. The modified correlation (Eqs. 4.1 and 4.2) has given satisfactory results. Similar modifications may be required for some of the other refrigerants.

For the case of horizontal flow, the data of Chawla (R-11), Mummm (water) and Gouse and Coumou (R-113) is well represented by Eqs. (3.7) and (3.8) with a correction factor representing the fraction of the tube circumference which remains dry. The correction factor is a function of the Froude number, for the case when the Froude number is less than 0.04. As no other data, except Chawla's was available in the above range of the Froude number, the correlation (Eqs. 3.7 and 3.8) needs further testing for the correction factor used.

In conclusion, the proposed correlation has given the best overall result for the data analyzed during this investigation when compared with other existing correlations. Further testing with more data is suggested before accepting it as a general correlation.

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APPENDIX A

The computer program and the results for the data of Chawla, J.M.,
R-11 boiling in horizontal tubes.

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1. REAL MUL,MUG,KL
2. DIMENSION X(181),HEXP(181),G(181),CD(181),Q(181),REL(181)
3. DIMENSION BO(181),FR(181),DI(181),PRL(181)
4. DIMENSION ROHL(181),ROHG(181),MUL(181),MUN(181),KL(181),CPL(181),
5. HFG(181),HPRED(181),ER1(181),HL(181)
6. N=181
7. DATA DI/84*0.,025,.31*0.,014,.68*0.,008/
8. DATA ROHL/51*1548.5,.33*1487.6,.97*1510.1/
9. DATA ROHG/51*2.438,.33*5.13,.97*3.579/
10. DATA MUL/51*0.000545,.33*0.0004414,.97*0.0004891/
11. DATA MUG/51*0.000099,.33*0.0000103,.97*0.00001025/
12. DATA KL/51*0.09426,.33*0.08037,.97*0.0915/
13. DATA CPL/51*866.8,.33*881.98,.97*874.5/
14. DATA HFG/51*188860.4,.33*181674.7,.97*185304.8/
15. DATA G/2*83.9,.3*98.2,.3*142.4,.151.9,.4*177.9,.2*200.4,.201.8,.205.3,.205
16. 1.3,207.7,77.9,110.4,140.8,182.1,68.2,76.8,100.3,139.1,172.2,48.6,
17. 195.6,126.3,181.3,168.2,50.8,97.1,106.,138.,180.6,50.8,73.7,98.9,
18. 1106.4,134.6,174.4,50.8,70.6,97.1,107.1,138.6,144.1,188.7,91.5,187.
19. 18,228.5,91.5,132.4,162.9,198.7,245.,64.3,123.2,163.8,215.4,288.1,
20. 191.6,148.8,159.4,232.9,87.2,133.5,154.5,214.1,232.9,246.8,264.9,
21. 1123.6,136.9,141.3,154.5,235.1,136.9,138.6,157.5,235.1,3*30.9,5*146
22. 1.1,5*30.9,5*47.9,5*142.4,4,4*57.4,4*130.2,5*19.8,5*17.2,7*23.8,8*36.
23. 16,7*56.5,4*11.03,6*33.5,3*13.2,3*17.7,3*24.1,4*9.,4*13.02,2*19.2,-
24. 13*20.5,2*27.1/
25. DATA X/.36,.55,.304,.34,.65,.39,.68,.8,.56,.26,.355,.635,.73,.65,
26. 1.73,.56,.148,.31,.4,4*.1,5*.3,5*.5,5*.9,.6*.7,.7*.8,.3*.1,5*.3,5*.5,
27. 14*.7,7*.8,5*.9,4*.95,8*.1,5*.5,10*.8,8*.9,5*.1,27*.1,10*.3,9*.7,
28. 14*.8,11*.8/
29. DATA Q/19*3.89,.32*.553,.33*.555,.369/.737,1.106,.369,1.106,2.212,
30. 13.687,5.53,.369,.737,1.475,2.212,3.687,.369,.737,1.475,2.212,3.6
31. 187,1.475,2.212,3.687,5.53,7.374,1.475,2.212,2.85,3.687,2.212,3.687
32. 1.5.53,7.374,.738,1.476,2.952,4.428,6.642,1.478,2.952,4.428,6.642,
33. 19.225,1.476,2.952,4.428,6.642,9.225,13.8,16.605,1.476,2.952,4.428,
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16.642,9.225,13.8,18.45,22.14,2.952,4.428,6.642,9.225,18.45,22.14,
35. - 129.52,2.214,2.952,4.428,8.642,2.952,4.428,8.642,9.225,13.8,18.45,
36. - 12.952,4.428,6.642,2.952,4.428,6.642,2.952,4.428,6.642,1.476,2.952,
37. - 14.428,6.642,1.476,2.952,4.428,6.642,3.69,4.428,6.642,
38. - 12.952,4.428/
39. DATA HEXP/97.1,93.2,94.4,93.6,91.3,90.3,95.2,94.1,99.1,99.7,
40. - 1105.6,111.6,117.3,124.5,111.6,100.8,103.2,103.2,38.9,39.1,32.8,34.
41. - 11.24.6,25.9,31.3,54.4,69.2,23.7,41.9,62.7,67.8,80.8,25.8,45.7,53.5,
42. - 182.7,111.7,25.7,44.7,54.9,60.9,74.1,103.3,25.8,41.8,52.8,62.7,74.9,
43. - 177.6,122.9,48.7,47.3,50.2,41.4,43.8,45.1,64.7,79.9,36.5,47.3,82.5,
44. - 1783.1,122.9,50.2,64.8,74.9,122.9,47.1,64.7,75.8,110.8,141.7,142.
45. - 17.153.6,56.4,61.4,62.7,74.3,134.7,54.3,57.3,62.7,93.,45.67,56.32,
46. - 170.66,136.6,126.6,146.02,181.86,267.3,54.7,52.8,54.7,88.1,117.8,
47. - 193.2,102.4,109.4,119.4,126.4,431.1,446.5,458.7,471.7,462.8,115.57,
48. - 1113.9,112.6,138.8,372.3,401.8,426.8,388.6,148.4,151.5,218.,284.,
49. - 1387.,195.9,244.5,313.3,402.4,475.2,292.9,301.,346.1,466.9,470.,
50. - 1569.3,610.3,365.5,348.2,434.2,487.4,476.2,529.4,626.7,653.3,473.,
51. - 11.514.,530.4,559.1,782.3,872.4,1103.9,208.9,229.,281.2,381.9,
52. - 1647.2,610.3,634.9,614.4,784.4,917.5,304.1,309.2,357.4,581.6,550.9,
53. - 1526.3,896.3,639.7,655.4,184.7,190.5,241.7,319.5,382.5,275.7,290.8,
54. - 1351.,757.8,692.2,981.,818.2,742.4,1310.7,1110.2/
55. DO 99 I=1,N
56. G(I)=G(I)/(3.141592774*DI(I)**2)*0.45359237/3600
57. Q(I)=Q(I)*10**3/3600*1054.35/(0.3048**2)
58. HEXP(I)=HEXP(I)*5.6783
59. PRL(I)=CPL(I)*MUL(I)/KL(I)
60. FR(I)=G(I)**2/(ROHL(I)**2*9.81*DI(I))
61. REL(I)=G(I)*(1-X(I))*DI(I)/MUL(I)
62. R0(I)=G(I)/(HFG(I)*G(I))
63. CO(I)=(1./X(I)-1)**8*(ROHL(I)/ROHL(I))**.5
64. CONTINUE
65. 99 FORMAT(//, R1 R2
66. 1 RMS ERROR //) MEAN ERROR

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6/.   821  WRITE(108,B21)
68.   821  FORMAT('      I      HEXP      BO #      HPRED      HL //',% ERROR
69.     1FR #      CO #      BO #      HPRED      HL //')
70.     R1=0.3
71.     R2=0.1
72.     ERROR=0.0
73.     RMSER=0.0
74.     DO 810 I=1,N
75.       HL(I)=0.023*REL(I)*#0.8*PRL(I)*#0.4*KL(I)/DI(I)
76.       HPRED(I)=HL(I)*(1.876*(1/CO(I))**0.79+0.7*(BO(I)**1.E4)**#0.9)
77.       IF(FR(I)>=0.04) GO TO 851
78.       HPRED(I)=HL(I)*(1.876*(1/CO(I))**0.79*(25*FR(I))**#R1+0.7*(BO(I)**1.E4)**#0.9*(25*FR(I))*#R2)
79.     851  CONTINUE
80.     IF(CO(I).LT.0.65) GO TO 871
81.     HPRED(I)=HL(I)*(0.533*(1./CO(I))*#0.79+2.3*(BO(I)**1.E4)**#0.5)
82.     871  CONTINUE
83.     ER1(I)=(HPRED(I)-HEXP(I))/HEXP(I)*100
84.     ERROR=ERROR+ABS(ER1(I))
85.     RMSER=RMSER+ER1(I)*ER1(I)
86.   333  FORMAT(14,7E13.5)
87.     WRITE(108,333) I,HEXP(I),HPRED(I),ER1(I),BO(I),HL(I)
88.     810  CONTINUE
89.     ERROR=ERROR/N
90.     RMSER=(RMSER/N)**0.5
91.     WRITE(108,860)
92.     WRITE(108,861) R1,R2,ERROR,RMSER
93.   861  FORMAT(2X,2F12.4,2E15.3)
94.     861  CONTINUE
95.     END
96.

```

I	HEXP	HRED	% ERROR	FR #	CO #	BO #	HL
1	.55136E 03	-4.2589E 03	-22757E 02	78864E -03	62873E -01	-28601E -02	-28763E 02
2	.52922E 03	.39191E 03	-.25946E 02	.78864E -03	.33794E -01	-.28601E -02	.21700E 02
3	.53603E 03	.47002E 03	-.12315E 02	.10804E -02	.76975E -01	-.24436E -02	.34896E 02
4	.53149E 03	.46816E 03	-.11916E 02	.10804E -02	.67455E -01	-.24436E -02	.33435E 02
5	.51843E 03	.41616E 03	-.19727E 02	.10804E -02	.24182E -01	-.24436E -02	.20129E 02
6	.55818E 03	.59981E 03	-.74584E 01	.22718E -02	.68921E -01	-.16851E -02	.45556E 02
7	.54057E 03	.58083E 03	-.74463E 01	.22718E -02	.21714E -01	-.16851E -02	.25224E 02
8	.53376E 03	.53797E 03	-.78832E 00	.22718E -02	.13089E -01	-.16851E -02	.17319E 02
9	.55704E 03	.63993E 03	-.14881E 02	.25851E -02	.32717E -01	-.15797E -02	.34268E 02
10	.56726E 03	.68986E 03	-.21613E 02	.355457E -02	.161615E -01	-.13489E -02	.58939E 02
11	.56613E 03	.72183E 03	-.27503E 02	.355457E -02	.63977E -01	-.13489E -02	.52804E 02
12	.59963E 03	.74273E 03	-.23065E 02	.355457E -02	.25479E -01	-.13489E -02	.33485E 02
13	.63370E 03	.72279E 03	-.14059E 02	.35457E -02	.17906E -01	-.13489E -02	.26309E 02
14	.66606E 03	.84372E 03	-.26673E 02	.44994E -02	.424182E -01	-.11974E -02	.35617E 02
15	.70695E 03	.82846E 03	-.17198E 02	.44994E -02	.17806E -01	-.11974E -02	.28939E 02
16	.63370E 03	.85197E 03	-.34444E 02	.45624E -02	.32717E -01	-.11891E -02	.43011E 02
17	.57237E 03	.69004E 03	-.20557E 02	.47221E -02	.16302E 00	-.11688E -02	.74124E 02
18	.58600E 03	.79967E 03	-.36482E 02	.47221E -02	.75258E -01	-.11688E -02	.62498E 02
19	.58600E 03	.84514E 03	-.44222E 02	.48331E -02	.54083E -01	-.11553E -02	.56409E 02
20	.22089E 03	.12848E 03	-.41833E 02	.67988E -03	.23012E 00	-.46164E -03	.35604E 02
21	.22202E 03	.17033E 03	-.23282E 02	.13655E -02	.23012E 00	-.32574E -03	.47060E 02
22	.10625E 03	.21351E 03	-.14637E 02	.22211E -02	.23012E 00	-.25541E -03	.57168E 02
23	.19363E 03	.27766E 03	-.43399E 02	.37151E -02	.23012E 00	-.19748E -03	.70230E 02
24	.13969E 03	.14883E 03	-.65492E 01	.49099E -03	.78152E -01	-.54323E -03	.25565E 02
25	.14650E 03	.17181E 03	-.17275E 02	.66081E -03	.78152E -01	-.46825E -03	.28790E 02
26	.17773E 03	.24923E 03	-.40229E 02	.13384E -02	.70152E -01	-.32902E -03	.38182E 02
27	.30890E 03	.32834E 03	-.62920E 01	.21678E -02	.78152E -01	-.25853E -03	.46304E 02
28	.39180E 03	.42410E 03	-.82421E 01	.33222E -02	.78152E -01	-.20884E -03	.54927E 02
29	.13458E 03	.12042E 03	-.10518E 02	.26462E -03	.39679E -01	-.73996E -03	.15253E 02
30	.23792E 03	.25143E 03	-.56784E 01	.10239E -02	.39679E -01	-.37617E -03	.26207E 02
31	.35603E 03	.35252E 03	-.98547E 00	.17872E -02	.39679E -01	-.28473E -03	.32747E 02
32	.38499E 03	.36997E 03	-.39001E 01	.19315E -02	.39679E -01	-.27389E -03	.33791E 02
33	.459337E 03	.50647E 03	-.10252E 02	.31696E -02	.39679E -01	-.21380E -03	.41183E 02

I	HEXP	H'PRED	% ERROR	FR #	CD #	BO #	HL
34	14536E 03	.10651E 03	-.26727E 02	.28912E-03	.68417E-02	.70791E-03	.43608E 01
35	.25950E 03	.24851E 03	-.42333E 01	.10563E-02	.68417E-02	.37036E-03	.73224E 01
36	.30379E 03	.27957E 03	-.79738E 01	.12588E-02	.68417E-02	.33926E-03	.78546E 01
37	.35603E 03	.39956E 03	-.12228E 02	.21336E-02	.68417E-02	.26059E-03	.97002E 01
38	.63029E 03	.57716E 03	-.84299E 01	.36542E-02	.68417E-02	.19912E-03	.12030E 02
39	.14593E 03	.12429E 03	-.14031E 02	.28912E-03	.20146E-01	.70791E-03	.10502E 02
40	.24985E 03	.19238E 03	-.23000E 02	.60884E-03	.20146E-01	.48795E-03	.14143E 02
41	.31174E 03	.27738E 03	-.11022E 02	.10958E-02	.20146E-01	.36362E-03	.17895E 02
42	.34581E 03	.30446E 03	-.11956E 02	.12683E-02	.20146E-01	.33799E-03	.18973E 02
43	.42076E 03	.41283E 03	-.18841E 01	.20298E-02	.20146E-01	.26718E-03	.22899E 02
44	.58657E 03	.58147E 03	-.86961E 00	.34076E-02	.20146E-01	.20620E-03	.28172E 02
45	.14650E 03	.11866E 03	-.19004E 02	.28912E-03	.13089E-01	.70791E-03	.75927E 01
46	.23735E 03	.17769E 03	-.25139E 02	.65842E-03	.13089E-01	.50938E-03	.98798E 01
47	.29868E 03	.26726E 03	-.10519E 02	.10563E-02	.13089E-01	.37036E-03	.12749E 02
48	.35603E 03	.30380E 03	-.14669E 02	.112051E-02	.13089E-01	.33578E-03	.13788E 02
49	.42530E 03	.42755E 03	-.52817E 00	.121522E-02	.13089E-01	.25947E-03	.16949E 02
50	.44064E 03	.45040E 03	-.22165E 01	.23264E-02	.13089E-01	.24958E-03	.17484E 02
51	.69786E 03	.64793E 03	-.71545E 01	.39893E-02	.13089E-01	.19058E-03	.21693E 02
52	.27256E 03	.13645E 03	-.49939E 02	.10164E-02	.34057E 00	.41005E-03	.42024E 02
53	.26858E 03	.22467E 03	-.16351E 02	.94181E-02	.34057E 00	.22360E-03	.69564E 02
54	.28505E 03	.30614E 03	-.73994E 01	.63384E-02	.34057E 00	.16420E-03	.89055E 02
55	.23508E 03	.18047E 03	-.23233E 02	.10164E-02	.11566E 00	.41005E-03	.35025E 02
56	.24871E 03	.26404E 03	-.81626E 01	.21280E-02	.11566E 00	.28338E-03	.47070E 02
57	.25609E 03	.33313E 03	-.30084E 02	.32214E-02	.11566E 00	.23032E-03	.55561E 02
58	.36739E 03	.42070E 03	-.14511E 02	.47929E-02	.11566E 00	.18883E-03	.65132E 02
59	.45370E 03	.54318E 03	-.19723E 02	.72866E-02	.11566E 00	.15314E-03	.77014E 02
60	.20726E 03	.20970E 03	-.11797E 01	.10795E 02	.58724E-01	.39787E-03	.27412E 02
61	.26858E 03	.28511E 03	-.61540E 01	.18426E-02	.58724E-01	.30454E-03	.33949E 02
62	.35489E 03	.40134E 03	-.13089E 02	.32373E-02	.58724E-01	.22976E-03	.42533E 02
63	.47187E 03	.56959E 03	-.20710E 02	.56324E-02	.58724E-01	.17419E-03	.53080E 02
64	.69786E 03	.83201E 03	-.18223E 02	.10076E-01	.58724E-01	.13023E-03	.66984E 02
65	.28505E 03	.20877E 03	-.26761E 02	.10106E-02	.29815E-01	.40960E-03	.17798E 02
66	.36795E 03	.38344E 03	-.42098E 01	.26879E-02	.29815E-01	.25215E-03	.26238E 02

I	HEXP	HRED	% ERROR	F#	CD #	BO #	HL
67	.42530E 03	.41919E 03	-.14388E 01	.30845E-02	.29815E-01	.23530E-03	.27723E 02
68	.69786E 03	.69131E 03	-.93889E 00	.65848E-02	.29815E-01	.16110E-03	.37548E 02
69	.26745E 03	.19102E 03	-.28575E 02	.92308E-03	.19372E-01	.43027E-03	.12371E 02
70	.36739E 03	.32972E 03	-.10253E 02	.21636E-02	.19372E-01	.28105E-03	.17393E 02
71	.43042E 03	.39966E 03	-.71465E 01	.28978E-02	.19372E-01	.24285E-03	.19549E 02
72	.67458E 03	.61826E 03	-.93486E 01	.55647E-02	.19372E-01	.17524E-03	.25379E 02
73	.80461E 03	.69276E 03	-.13801E 02	.65848E-02	.19372E-01	.16110E-03	.27147E 02
74	.81029E 03	.74941E 03	-.75136E 01	.73943E-02	.19372E-01	.15202E-03	.28435E 02
75	.87219E 03	.82509E 03	-.53999E 01	.85186E-02	.19372E-01	.14164E-03	.30092E 02
76	.32026E 03	.27712E 03	-.13469E 02	.18546E-02	.10126E-01	.30356E-03	.93929E 01
77	.34865E 03	.31786E 03	-.80299E 01	.22752E-02	.10126E-01	.27407E-03	.10192E 02
78	.35603E 03	.33170E 03	-.68343E 01	.24238E-02	.10126E-01	.26553E-03	.10454E 02
79	.42190E 03	.37422E 03	-.11301E 02	.28978E-02	.10126E-01	.24285E-03	.11228E 02
80	.76487E 03	.66340E 03	-.13266E 02	.67098E-02	.10126E-01	.15959E-03	.15709E 02
81	.30833E 03	.28816E 03	-.65436E 01	.22752E-02	.55694E-02	.27407E-03	.58540E 01
82	.32537E 03	.29305E 03	-.99310E 01	.24320E-02	.55894E-02	.27070E-03	.59121E 01
83	.35603E 03	.34001E 03	-.45003E 01	.28978E-02	.55694E-02	.24285E-03	.64488E 01
84	.52808E 03	.60614E 03	-.14782E 02	.07088E-02	.55694E-02	.15959E-03	.90227E 01
85	.25933E 03	.16220E 03	-.37455E 02	.20424E-02	.28234E 00	.24821E-03	.49672E 02
86	.31980E 03	.21275E 03	-.33474E 02	.20424E-02	.28234E 00	.49574E-03	.49672E 02
87	.40123E 03	.26085E 03	-.34986E 02	.20424E-02	.28234E 00	.74395E-03	.49672E 02
88	.77566E 03	.94444E 03	-.21760E 02	.45659E-01	.28234E 00	.52486E-04	.17213E 03
89	.71887E 03	.10582E 04	-.47197E 02	.45659E-01	.28234E 00	.15735E-03	.17213E 03
90	.82915E 03	.12151E 04	-.46546E 02	.45659E-01	.28234E 00	.31469E-03	.17213E 03
91	.10327E 04	.14125E 04	-.36780E 02	.45659E-01	.28234E 00	.52453E-03	.17213E 03
92	.15178E 04	.16482E 04	-.85928E 01	.45659E-01	.28234E 00	.78673E-03	.17213E 03
93	.31060E 03	.29630E 03	-.46051E 01	.20424E-02	.48683E-01	.24821E-03	.31038E 02
94	.29981E 03	.32789E 03	-.93639E 01	.20424E-02	.48683E-01	.49574E-03	.31038E 02
95	.31060E 03	.38700E 03	-.24595E 02	.20424E-02	.48683E-01	.99216E-03	.31038E 02
96	.50026E 03	.44301E 03	-.11444E 02	.20424E-02	.48683E-01	.14879E-02	.31038E 02
97	.66890E 03	.55001E 03	-.17775E 02	.20424E-02	.48683E-01	.24801E-02	.31038E 02
98	.52922E 03	.57196E 03	-.80764E 01	.49079E-02	.16059E-01	.16012E-03	.21176E 02
99	.58146E 03	.58782E 03	-.10936E 01	.49079E-02	.16059E-01	.31980E-03	.21176E 02
100	.62121E 03	.61749E 03	-.59852E 00	.49079E-02	.16059E-01	.64004E-03	.21176E 02

I HEXP HPRED % ERROR FR # CO # BO # HL

101	.67799E 03	.64560E 03	-.47765E 01	.49079E-02	.16059E-01	.95984E-03	.21176E 02
102	.71774E 03	.69931E-03	-.25867E 01	.48079E-02	.16059E-01	.15999E-02	.21176E 02
103	.24479E 04	.25543E 04	.43457E 01	.43376E-01	.16059E-01	.21529E-03	.50627E 02
104	.25354E 04	.25854E 04	.19735E 01	.43376E-01	.16059E-01	.32287E-03	.50627E 02
105	.26046E 04	.26448E 04	.15422E 01	.43376E-01	.16059E-01	.53816E-03	.50627E 02
106	.26745E 04	.27158E 04	.15438E 01	.43376E-01	.16059E-01	.80717E-03	.50627E 02
107	.26279E 04	.27844E 04	.59544E 01	.43376E-01	.16059E-01	.10763E-02	.50627E 02
108	.65584E 03	.72121E 03	.99673E 01	.70477E-02	.83943E-02	.53411E-03	.14057E 02
109	.64676E 03	.73766E 03	.14055E 02	.70477E-02	.83943E-02	.80098E-03	.14057E 02
110	.63938E 03	.75357E 03	.17860E 02	.70477E-02	.83943E-02	.10682E-02	.14057E 02
111	.77679E 03	.76907E 03	.99414E 00	.70477E-02	.83943E-02	.13351E-02	.14057E 02
112	.21140E 04	.22109E 04	.45814E 01	.36262E-01	.83943E-02	.35312E-03	.27067E 02
113	.22804E 04	.22450E 04	.-15536E 01	.36262E-01	.83943E-02	.58859E-03	.27067E 02
114	.24224E 04	.22857E 04	.-56418E 01	.36262E-01	.83943E-02	.88280E-03	.27067E 02
115	.22690E 04	.23251E 04	.-24694E 01	.36262E-01	.83943E-02	.11772E-02	.27067E 02
116	.83130E 03	.70328E 03	-.15400E 02	.28175E-01	.20234E 00	.20416E-03	.11979E 03
117	.86026E 03	.83658E 03	-.27534E 01	.28175E-01	.28234E 00	.40832E-03	.11979E 03
118	.12379E 04	.10853E 04	-.12324E 02	.28175E-01	.328234E 00	.81664E-03	.11979E 03
119	.16126E 04	.13213E 04	-.18064E 02	.28175E-01	.28234E 00	.12250E-02	.11979E 03
120	.21975E 04	.18613E 04	-.24401E 02	.28175E-01	.28234E 00	.18374E-02	.11979E 03
121	.11124E 04	.10198E 04	-.84106E 01	.43769E-01	.28234E 00	.32761E-03	.14286E 03
122	.13883E 04	.12708E 04	-.84654E 01	.43769E-01	.28234E 00	.65521E-03	.14286E 03
123	.17790E 04	.15098E 04	-.15125E 02	.43769E-01	.28234E 00	.98282E-03	.14286E 03
124	.22849E 04	.18544E 04	-.18845E 02	.43769E-01	.28234E 00	.14742E-02	.14286E 03
125	.26983E 04	.22419E 04	-.16916E 02	.43769E-01	.28234E 00	.20475E-02	.14286E 03
126	.16632E 04	.12255E 04	-.26317E 02	.83804E-01	.28234E 00	.23676E-03	.18525E 03
127	.17092E 04	.14694E 04	-.14027E 02	.83804E-01	.28234E 00	.47352E-03	.18525E 03
128	.19653E 04	.17009E 04	-.13452E 02	.83804E-01	.28234E 00	.71027E-03	.18525E 03
129	.26512E 04	.20343E 04	-.23268E 02	.83804E-01	.28234E 00	.10654E-02	.18525E 03
130	.26680E 04	.24094E 04	-.97180E 01	.83804E-01	.28234E 00	.14797E-02	.18525E 03
131	.32327E 04	.30498E 04	-.56580E 01	.83804E-01	.28234E 00	.22136E-02	.18525E 03
132	.34655E 04	.34314E 04	-.98445E 00	.83804E-01	.28234E 00	.266635E-02	.18525E 03
133	.20754E 04	.16015E 04	-.22835E 02	.19819E 00	.28234E 00	.15399E-03	.26139E 03

I	HEXP	HRED	% ERROR	FR #	CO #	80 #	HL
134	.19772E 04	.18352E 04	-.71826E 01	-19819E 00	.20234E 00	.30791E-03	.26139E 03
135	.24655E -04	.20569E 04	-.16573E 02	-.10819E 00	.20234E 00	.46187E-03	.26139E 03
136	.27676E 04	.23763E 04	-.14140E 02	.10819E 00	.20234E 00	.69281E-03	.26139E 03
137	.27040E 04	.27356E 04	-.11684E 01	.10819E 00	.20234E 00	.96223E-03	.26139E 03
138	.30061E 04	.33489E 04	-.11405E 02	.10819E 00	.20234E 00	.14394E-02	.26139E 03
139	.35586E 04	.39515E 04	-.11040E 02	.10819E 00	.20234E 00	.19245E-02	.26139E 03
140	.37096E 04	.44186E 04	-.19112E 02	.10819E 00	.20234E 00	.23094E-02	.26139E 03
141	.26864E 04	.23669E -04	-.11895E 02	.47228E 00	.20234E 00	.19946E-03	.36995E 03
142	.29106E 04	.25792E 04	-.11632E 02	.47229E 00	.20234E 00	.29919E-03	.36995E 03
143	.30118E 04	.28850E 04	-.42103E 01	.47229E 00	.20234E 00	.44879E-03	.36995E 03
144	.31747E 04	.32290E 04	-.17101E 01	.47229E 00	.20234E 00	.62332E-03	.36995E 03
145	.44421E 04	.43932E 04	-.11009E 01	.47229E 00	.20234E 00	.12466E-02	.36995E 03
146	.49537E 04	.48405E 04	-.22054E 01	.47229E 00	.20234E 00	.14960E-02	.36995E 03
147	.62683E -04	.57140E -04	-.88421E -01	.47229E 00	.20234E 00	.19946E-02	.36995E 03
148	.11862E 04	.11015E 04	-.71423E 01	.10000E-01	.95887E-01	.76630E-03	.81893E 02
149	.13003E 04	.11892E 04	-.77398E 01	.10000E-01	.95887E-01	.10217E-02	.81893E 02
150	.15967E -04	.13880E -04	-.13078E 02	.10000E-01	.95887E-01	.15326E-02	.81893E 02
151	.21685E 04	.16599E 04	-.23456E 02	.10000E-01	.95887E-01	.22989E-02	.81893E 02
152	.36750E 04	.27970E 04	-.23891E 02	.16603E 00	.95887E-01	.33641E-03	.19917E 03
153	.34655E 04	.29800E -04	-.14010E 02	.16603E 00	.95887E-01	.50461E-03	.19917E 03
154	.36052E 04	.32435E 04	-.10032E 02	.16603E 00	.95887E-01	.75692E-03	.19917E 03
155	.34887E 04	.35400E 04	-.14086E 01	.16603E 00	.95887E-01	.10513E-02	.19917E 03
156	.44541E 04	.40461E 04	-.91598E 01	.16603E 00	.95887E-01	.15726E-02	.19917E 03
157	.52098E 04	.45432E 04	-.12795E 02	.16603E 00	.95887E-01	.21025E-02	.19917E 03
158	.17268E 04	.16898E 04	-.21433E 01	.25779E-01	.24717E-01	.85376E-03	.48002E 02
159	.17557E 04	.17873E 04	-.18001E -01	.25779E-01	.24717E-01	.12806E-02	.48002E 02
160	.20294E 04	.19279E 04	-.50037E 01	.25779E-01	.24717E-01	.19210E-02	.48002E 02
161	.33025E 04	.23429E 04	-.29056E 02	.46351E-01	.24717E-01	.63670E-03	.60699E 02
162	.31282E 04	.24416E 04	-.21938E 02	.46351E-01	.24717E-01	.95506E-03	.60699E 02
163	.29885E 04	.25845E 04	-.13517E 02	.46351E-01	.24717E-01	.14326E-02	.60699E 02
164	.39530E 04	.29293E 04	-.25911E 02	.85930E-01	.24717E-01	.46762E-03	.77699E 02
165	.36284E 04	.30253E 04	-.16622E 02	.85930E-01	.24717E-01	.70143E-03	.77699E 02
166	.37216E 04	.31636E 04	-.14993E 02	.85930E-01	.24717E-01	.10521E-02	.77699E 02

	R1	R2	MEAN'ÉRRRIR	RMB ERROR
STOPP	.3000	.1000	.151E 02	.195E 02

APPENDIX B

The computer program and the results for the data of Jallouk, P.A.,
R-114 boiling in vertical tube.

```

1.      REAL MUL,MUG,KL
2.      DIMENSION X(045),HEXP(045),G(045),CO(045),B(045),REL(045)
3.      DIMENSION BD(045),FR(045),DI(045),PRL(045),
4.      DIMENSION ROHL(045),ROHG(045),MUL(045),MUG(045),KL(045),CPL(045),
5.      HF(045),HPRED(045),ER1(045)
6.      DIMENSION X1(045),X2(045),HL(045)
7.      N=045
8.      DATA DI/45*0,0.0654/
9.      DATA ROHL/88.199,88.308,88.332,88.392,88.440,88.488,88.537,
10.      188.151,88.259,88.235,88.271,88.282,88.344,88.344,88.067
11.      1,82.309,82.297,82.297,82.369,82.381,82.381,82.477,82.477,
12.      182.441,82.429,82.501,82.514,82.369,82.471,82.514,82.501,
13.      182.477,82.429,82.501,82.526,75.043,75.057,75.202,75.187,
14.      175.115,75.075,75.173,75.159,75.130,75.144,
15.      DATA ROHG/1.48996,1.46118,1.45577,1.44631,1.41561,1.40335,
16.      11.5019,1.4742,1.4803,1.4711,1.4680,1.4526,1.45235
17.      1,2.996,2.999,2.999,2.981,2.978,2.978,2.967,
18.      12.962,2.966,2.947,2.944,2.944,2.944,2.944,2.947,
19.      12.977,2.966,2.947,2.941,5.768,5.763,5.708,5.713,
20.      15.741,5.763,5.719,5.723,5.735,5.730,
21.      DATA MUL/0.706770.709770.7103,0.7117,0.7133,0.7147,0.7160
22.      1.0.7053,0.7083,0.7077,0.7087,0.7090,0.7107,0.7107,0.7030
23.      1,.5435,.5432,.5432,.5452,.5455,.5455,.5482,.5479,
24.      1.5472,.5469,.5489,.5492,.5452,1.5465,.5469,.5489,
25.      1.5482,.5469,.5489,.5495,.4340,.4342,.4364,.4362,
26.      1.4351,.4342,.4360,.4357,.4353,.4355,
27.      DATA MUG/15*0.029208,20*0.031676,10*0.035506/
28.      DATA KL/15*0.0353,20*0.031197,10*0.026664/
29.      DATA CPL/15*0.24886,20*0.2646,10*0.28133/
30.      DATA HF/52.711,52.814,52.837,52.894,52.839,52.885,53.031,
31.      152.665,52.768,52.745,52.779,52.848,52.848,52.848,52.595

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32. 1,47,129,47,117,47,117,47,106,47,197,47,197,47,280,47,277,
33. 147,254,47,243,47,311,47,323,47,186,47,231,47,233,47,311,
34. 147,288,47,243,47,311,47,334,40,049,40,063,40,204,
35. 140,190,40,120,40,063,40,176,40,182,40,134,40,148/
36. DATA Q/7*119700,7*136000,119700
37. 1,5*144400,7*134500,8*143800,8*131000,2*132600/
38. DATA X1/0.024,0.058,0.092,0.158,0.192,0.224,0.256,
39. 10.025,0.079,0.134,0.246,0.301,0.356,0.411,0.611
40. 1.,015,..073,..103,..134,..164,..032,0.097,0.162
41. 1.,285,..347,..408,..47,..008,..055,..142,..229,
42. 1.,401,..487,..571,..655,..022,..055,..094,..131,
43. 1.,203,..237,..273,..309,..095,..226/
44. DATA X2/0.058,0.092,0.125,0.192,0.224,0.256,0.287,
45. 10.079,0.134,0.189,0.301,0.356,0.411,0.465,0.618
46. 1.,044,..103,..134,..164,..192,..097,..162,..223,
47. 1.347,..408,..470,..528,..055,..142,..229,..315,
48. 1.,487,..571,..655,..738,..055,..094,..151,
49. 1.,167,..237,..273,..304,..342,..226,..372/
50. DATA Q/3066.5,3308.8,3367.7,3618.6,2982.1,3105.7,3109.5,
51. 16237.2,6055.6,6811.5,6357.9,6263.7,6415.0,6205.3,6811.7
52. 1,3217.2,3451.4,3288.5,2999.7,3067.0,6603.3,6494.4,6414.8,
53. 16229.1,6321.4,6352.2,5898.9,9267.8,9251.0,9596.4,9567.3,
54. 19568.6,9188.5,9288.5,9065.5,2847.4,3103.5,2947.1,3143.1,
55. 13256.2,2854.2,3090.2,2770.7,12554.3,12370.9/
56. DATA HEXP/402.9,392.0,380.0,411.0,391.0,2,323.7,310.8/
57. 1406.4,435.9,489.7,450.6,416.2,414.5,425.3,609.9
58. 1,501.0,663.9,525.9,430.0,453.1,733.6,652.6,660.2,
59. 1735.8,644.5,576.4,573.9,861.7,838.8,774.2,813.4,
60. 1863.0,737.5,680.6,710.0,719.7,739.1,7542.0,607.3,
61. 1770.1,619.3,543.0,525.0,1102.1,1042.2/
62. DO 89 I=1,N

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53.  
X(I)=(X1(I)+X2(I))/2  
PRL(I)=CPL(I)*MUL(I)/KL(I)  
REL(I)=G(I)*(1-X(I))*DI(I)/MUL(I)  
BO(I)=Q(I)/(HFG(I)*G(I))  
CO(I)=(1./X(I)-1)**.8*(ROHG(I)/ROHL(I))**.5  
CONTINUE  
860 FORMAT(//,  
        WRITE(108,821)  
821 FORMAT(' I HEXP HPRED %7.7f %7.7f %7.7f')  
        ERROR=0.0  
        RMSER=0.0  
        DO 810 I=1,N  
        HL(I)=0.023*REL(I)**0.8*PRL(I)**0.4*KL(I)/DI(I)  
        HPRED(I)=HL(I)*(1.876*(1./CO(I))**0.79+1.547*(BO(I)*1.E4)**0.9)  
        IF(CO(I).LT.0.65) GO TO 871  
        HPRED(I)=HL(I)*(0.533*(1./CO(I))**0.79+5.08*(BO(I)*10**4)**0.5)  
        CONTINUE  
871 ER1(I)=(HPRED(I)-HEXP(I))/HEXP(I)**100  
        ERROR=ERROR+ABS(ER1(I))  
        RMSER=RMSE+ER1(I)*ER1(I)  
333 FORMAT(14,SE15.5)  
        WRITE(108,333) I,HEXP(I),HPRED(I),ER1(I),CO(I),HL(I)  
        CONTINUE  
        ERROR=ERROR/N  
        RMSER=(RMSE/N)**0.5  
860 WRITE(108,860)  
        WRITE(108,861) ERROR,RMSER  
        FORMAT(20X,2E15.3)  
801 CONTINUE  
END
```

I	HEXP	HRED	χ^2	ERROR	DO #	CD #	HL
1	40290E 03	.45393E 03	1.2665E 02	.49601E-03	.16182E 01	.39255E 02	
2	39200E 03	.46344E 03	1.0224E 02	.52339E-03	.96008E 00	.38073E 02	
3	39000E-03	.45952E-03	1.17825E 02	.53248E-03	.69220E 00	.36953E 02	
4	41130E 03	.38195E 03	-71359E 01	.57122E-03	.44010E 00	.34687E 02	
5	31820E 03	.34745E 03	91910E 01	.47060E-03	.436966E 00	.33559E 02	
6	32370E-03	.36498E-03	12752E 02	.50229E-03	.31806E 00	.32444E 02	
7	31980E 03	.36458E 03	14001E 02	.40985E-03	.27729E 00	.31341E 02	
8	48640E 03	.66460E 03	36636E 02	.870825E-03	.13315E 01	.43111E 02	
9	43590E-03	.63443E 03	.45545E-02	.84382E-03	.70859E 00	.41047E 02	
10	48970E 03	.58767E 03	20006E 02	.94956E-03	.48375E 00	.39026E 02	
11	45060E 03	.56044E 03	24375E 02	.88567E-03	.428206E 00	.34777E 02	
12	41620E 03	.55144E 03	32495E 02	.67243E-03	.22847E 00	.32649E 02	
13	41450E 03	.55240E 03	33270E 02	.89254E-03	.418746E 00	.30462E 02	
14	42530E 03	.53423E 03	25612E 02	.86337E-03	.15653E 00	.28288E 02	
15	60990E 03	.75621E 03	23990E 02	.13999E-02	.112095E 01	.38894E 02	
16	50100E 03	.54816E 03	.54125E 01	.47274E-03	.31209E 01	.48673E 02	
17	66390E 03	.55093E 03	.17031E 02	.50728E-03	.12394E 01	.46321E 02	
18	52590E 03	.52845E-03	.48540E 00	.48334E-03	.195060E 00	.45078E 02	
19	43000E 03	.49521E 03	.15166E 02	.44029E-03	.76682E 00	.43761E 02	
20	45310E 03	.36755E 03	.16880E 02	.45002E-03	.64656E 00	.42555E 02	
21	73360E 03	.74680E 03	.17989E 01	.10402E-02	.16152E 01	.44587E 02	
22	65260E 03	.70685E 03	.82130E 01	.10211E-02	.87241E 00	.42008E 02	
23	66820E 03	.60159E 03	.896691E 01	.10088E-02	.59726E 00	.39566E 02	
24	73580E 03	.56683E 03	.22964E 02	.96009E-03	.35157E 00	.34664E 02	
25	64450E 03	.55679E 03	.13609E 02	.99484E-03	.28302E 00	.32154E 02	
26	57640E 03	.53948E 03	.64061E 01	.99025E-03	.22996E 00	.29544E 02	
27	57390E 03	.49797E 03	.13231E 02	.92669E-03	.18949E 00	.26982E 02	
28	86170E 03	.91909E 03	.66589E 01	.13658E-02	.29480E 01	.48370E 02	
29	83860E 03	.87782E 03	.46768E 01	.13621E-02	.11193E 01	.45631E 02	
30	77420E 03	.81900E 03	.58694E 01	.14129E-02	.61694E 00	.41999E 02	
31	81340E 03	.76534E 03	.34496E 01	.14063E-02	.41544E 00	.38391E 02	

I	HEXP	HPRED	χ^2	ERRDR	BB #	CD #	HL
32	.86300E 03	.70449E 03	-.18368E 02	-.14071E -02	-.22744E 00		.30960E 02
33	.73750E 03	.64134E 03	-.13038E 02	-.13525E -02	-.17286E 00		.27138E 02
34	.68060E 03	.59327E 03	-.12831E 02	-.19853E -02	-.13082E 00		.23158E 02
35	.71000E 03	.52866E 03	-.25540E 02	-.13319E -02	-.87127E -01		.19057E 02
36	.71970E 03	.54851E 03	-.23786E 02	-.54273E -02	-.36379E 01		.45607E 02
37	.73910E 03	.55956E 03	-.24292E 02	-.59130E -02	-.20787E 01		.44228E 02
38	.54200E 03	.52121E 03	-.38360E 01	-.54058E -03	-.14379E 01		.42683E 02
39	.60730E 03	.53262E 03	-.12297E 02	-.59699E -03	-.11111E 01		.41280E 02
40	.77010E 03	.51281E 03	-.33410E 02	-.61955E -03	-.76097E 00		.38540E 02
41	.61930E 03	.46821E 03	-.24396E 02	-.54304E -03	-.65323E 00		.37181E 02
42	.54300E 03	.37721E 03	-.30532E 02	-.58715E -03	-.56787E 00		.55778E 02
43	.52500E 03	.34885E 03	-.33552E 02	-.52663E -03	-.49427E 00		.34291E 02
44	.11021E 04	.10395E 04	-.56776E 01	-.23590E -02	-.10380E 01		.41266E 02
45	.10422E 04	.10455E 04	-.31575E 00	-.23238E -02	-.54597E 00		.35716E 02

MEAN ERROR RMS ERROR

STOP 0 .167E 02 .199E 02