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Generalized CHF Prediction for Horizontal Tubes
with
Uniform Heat Flux

by

Y.L. Wong

Submitted to the Faculty of Engineering
of the University of Ottawa
in partial fulfilment of the requirements for the degree of

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in
Mechanical Engineering

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ABSTRACT

Accurate prediction of the Critical Heat Flux (CHF) or the heat flux associated with 'DNB' and 'Dryout' is of paramount importance in nuclear reactor design, reactor safety analysis and in the design of industrial boilers and heat exchangers involving two-phase flow. CHF in forced convective boiling was studied for both vertical and horizontal orientation. It is shown to be a complicated function of pressure, mass flux, hydraulic equivalent diameter and vapour quality. CHF due to phase separation and due to annular liquid film failure were analyzed. In horizontal, uniformly heated tubes, CHF was found to be lower than that for vertical upward flow under otherwise identical flow conditions. In light of the lack of a generalized prediction method for horizontal CHF, a semi-empirical correlation was developed and is capable of predicting both the upstream and downstream CHF for horizontal flow with uniform heat flux.

'Generalized Property Code' developed during the course of this study was found to be useful in predicting thermodynamic and transport properties of non-aqueous fluids and is suitable for thermalhydraulic analysis.

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NOMENCLATURE

		UNITS
A	Flow area	m^2
Bo	Bond number as defined in Eq. (2.19)	
CHF	Critical heat flux	$kW.m^{-2}$
$CHFR$	Horizontal to vertical critical heat flux ratio	
C_p	Specific heat capacity at constant pressure	$J.kg^{-1}.^{\circ}C^{-1}$
D	Tube diameter	m
d_D	Bubble departure diameter	m
d	Average bubble or droplet diameter	m
F_B	Buoyancy force acting on bubbles or droplets	N
F_D	Drag force acting on bubbles or droplets	N
F_T	Turbulent force acting on bubbles or droplets	N
Fr	Froude number as defined in Eq. (5.5)	
Fr^*	Modified Froude number as defined in Eq. (6.4)	
f	Friction factor	
G	Mass flux	$kg.m^{-2}.s^{-1}$
G_1	Lower mass flux threshold as defined in Eq. (5.4)	$kg.m^{-2}.s^{-1}$
G_2	Upper mass flux threshold as defined in Eq. (5.2)	$kg.m^{-2}.s^{-1}$
g	Acceleration due to gravity	$m.s^{-2}$
H_{fg}	Enthalpy of vaporization	$J.kg^{-1}$
K_s	Stratification factor for horizontal CHF	
L_h	Heated length of tube	m
M	Molecular weight	$kg.kgmole^{-1}$
P	Pressure	Pa
p	perimeter	m
P_c	Critical pressure	Pa

Pe	Peclet number, GDC_p/λ_L	
q	Heat flux	$kW.m^{-2}$
R	Universal gas constant	$J.molc^{-1}.K^{-1}$
Re_L	Reynold number for liquid, $GD(1 - X)/\mu_f$	
T	Temperature	$^{\circ}C, K$
T_1	Force balance parameter as defined in Eq. (5.18)	
T_2	Force balance parameter as defined in Eq. (5.20)	
T_3	Force balance parameter as defined in Eq. (5.27)	
T_4	Force balance parameter as defined in Eq. (5.32)	
T_5	Transit time ratio as defined in Eq. (5.40)	
T_6	Transit time ratio as defined in Eq. (5.48)	
T_c	Critical temperature	$^{\circ}C, K$
T^+	Dimensionless parameter as defined in Eq. (5.1)	
U	Phase velocity	$m.s^{-1}$
u	Phase velocity	$m.s^{-1}$
V	Molar volume	$m^3.kgmole^{-1}$
V_c	Critical molar volume	$m^3.kgmole^{-1}$
v'	Radial fluctuating velocity	$m.s^{-1}$
X	Vapour quality	
X_e	Equilibrium quality	
X_{ed}	Equilibrium quality at bubble departure	
X	Lockhart-Martinelli parameter	
Y	Ratio of vapour to liquid volumetric void fraction	
Z	Compressibility factor, PV/RT , Ohnesorge number	
Z_c	Critical compressibility factor, $P_c V_c / RT_c$	

Greek Symbols

α	Void fraction
----------	---------------

β	Volumetric flow fraction	
β_0	Contact angle	
Δ	Change in	
ΔH_{in}	Inlet subcooling	$J.kg^{-1}$
λ	Thermal conductivity	$W.m^{-1}.K^{-1}$
μ	Viscosity	$kg.m^{-1}.s^{-1}$
θ	Parameter relating surface tension to the normal boiling point of the substance	
ρ	Density	$kg.m^{-3}$
σ	Surface tension	$N.m^{-1}$
ψ_H	Merilo's CHF modeling parameter	
ω	Acentric factor of the substance	

Subscripts

c	Critical
cr	Critical
$expt$	experimental
f	Saturated liquid
G	Vapour phase
g	Saturated vapour
hor	Horizontal
i	interface
in	Inlet
L	Liquid phase
$pred$	Predicted*
r	Reduced
ver	Vertical



Superscripts

- Dimensionless parameter

+ Dimensionless parameter

Chapter 1

INTRODUCTION

In most reactor and boiler systems, the energy transport involves various kinds of boiling heat transfer in two-phase flow. In two-phase heat transfer, boiling crisis is a very important phenomenon for the thermalhydraulic analysis. Figure 1 shows a typical boiling curve for two-phase flow. As can be seen from the figure, boiling crisis is one of the transition points between different heat transfer regimes.

Accurate prediction of the heat flux associated with the boiling crisis or critical heat flux (CHF) is of paramount importance in reactor design and reactor safety analysis. It is also of equal importance in devices operating under subcooled or non-boiling conditions such as in PWR. Boiling may occur under off design conditions or accident conditions in systems which are normally non-boiling and thus CHF may occur. CHF may also occur in other two-phase flow equipment such as conventional boiler systems, distillation and condensation equipment.

Over the years, hundreds of ad hoc correlations have been developed for the prediction of CHF in both vertical and horizontal tube flows. Most of them are for vertical flow and they are only applicable for a limited range of flow parameters. Recently, Groeneveld et al.(1986a) have published a generalized CHF table for vertical tube flow. This table is also applicable for non-aqueous fluids and for bundle geometries. Assessment of various published correlations undertaken by the ESDU (1986) shows this tabular method to be the best of the published methods. However, a similar ap-

proach for prediction of CHF in horizontal flow is not available. This is because of the scarcity of experimental CHF data, and because the mechanisms controlling CHF in horizontal flow are less understood than those for vertical flow.

This study is aimed at the development of a generalized semi-analytical prediction of CHF for horizontal flow. Only the CHF for horizontal tubes with uniform heat flux is considered in this study. Sources of experimental data are obtained from Merilo (1977), Merilo and Ahmad (1979), Robertson (1973), Becker (1971), Leontiev et al. (1981), Lis and Strickland (1970), Kohler and Hein (1986), Rounthwaite (1968), Ishigai and Takagi (1970a) and Wang and Su (1980). Some of the data (those from Lis and Strickland, Wang and Su and Ishigai and Takagi) were not used in the derivation of the present correlation.

The mechanisms of CHF for both vertical and horizontal flow are discussed in Chapter 2. Some CHF prediction methods available in the literature will also be introduced. In Chapter 3, sources of experimental CHF data are outlined and the experimental data is analysed to show the CHF trends with quality, mass velocity, tube diameter and pressure. The experimental data was compiled and arranged in a tabular format and is presented in Appendix A.

A generalized property code for non-aqueous fluids has also been developed for the purpose of fluid property evaluations. The code will permit the evaluation of CHF in horizontal flow for all transport properties for that fluid. The code predicts the properties including specific volume, specific enthalpy, specific heat, viscosity, thermal conductivity and surface tension. The development of this property code is presented in Chapter 4 and the source code can be found in Appendix B.

In Chapter 5, analytical expressions have been derived considering the turbulent-gravity force balance and bubbles or droplets transit time ratio. The dimensionless parameters developed can be treated as measures of the degree of stratification for two phase flow and will be used subsequently in the derivation of stratification factor for horizontal CHF. The derivation of the stratification factor is presented in Chapter 6 with assessment technique and comparison to experimental data. The parametric

trends of the new CHF correlation have been summarized and shown to be consistent with the experimental trends.

Chapter 2

TWO-PHASE FLOW AND CRITICAL HEAT FLUX

2.1 Flow Regimes in Two-Phase Flow

In gas-liquid flow the two phases can distribute themselves in the conduit in a wide variety of ways. The phase distribution will affect the evaluation of two-phase thermalhydraulic quantities such as the void fraction, pressure drop and heat transfer in general. The phase distribution forms a number of interesting patterns called flow regimes. A particular flow regime is dependent on a number of flow parameters such as the mass flux (G), vapour quality (X), pressure (P) and the tube diameter (D). The flow regimes also vary with the tube orientation. The designation of the flow regimes is more of a subjective judgement than an objective measurement. In this thesis, only the commonly distinguishable flow regimes encountered in vertical and horizontal tubes will be discussed.

2.1.1 Flow Regimes in Vertical Flow

For vertical upward flow, there are basically five distinguishable flow regimes. They are the bubbly flow, slug flow, churn flow, wispy-annular flow and annular flow. The schematic diagram for the flow regimes encountered in vertical flow is shown in figure 2.

Bubbly Flow

In bubbly flow, the gas phase is distributed in the form of discrete bubbles completely entrained in the liquid stream. The bubbles are of approximately uniform size.

Slug Flow

In this flow regime, large bullet-shaped bubbles (slugs) are found and are separated from the tube wall by the descending film of liquid. Also, the successive vapour slugs are separated by the liquid slugs which may or may not contain smaller gas bubbles.

Churn Flow

Churn flow is very chaotic and turbulent. It is formed by the breakdown of the large vapour bubbles in slug flow (Collier, 1981). The main characteristic of the churn flow is the oscillatory or alternating direction of motion of the liquid.

Wispy-Annular Flow

Wispy-annular flow regime was first identified by Hewitt et al. (1970). In this flow regime, relatively thick liquid film flows along the tube wall together with a considerable amount of liquid entrained in the gas core. Small bubbles are found in the liquid film. This flow regime is found to occur with high mass velocities.

Annular Flow

Annular flow is characterized by continuity in the axial direction of the gas phase in the core. Similar to the wispy-annular flow, the liquid film is flowing on the tube wall with little bubble entrainment. Separated droplets are entrainment in the gas core in varying amount.

2.1.2 Flow Regimes in Horizontal Flow

For horizontal flow, the flow regimes are complicated by the asymmetry of the two-phase distribution due to the influence of gravity in the transverse direction to the flow. Figure 3 shows the generally recognised flow regimes.

Bubbly Flow

The flow pattern in this regime is similar to that in vertical flow except that the vapour phase (bubble) tends to flow along the top part of the tube. At moderate and high mass velocities, the vapour and liquid phases distribute themselves more symmetrically and hence the flow pattern resembles that in vertical flow.

Plug Flow

Plug flow is similar to the slug flow in the vertical direction except that the gas bubbles tend to travel in the upper half of the tube.

Stratified Flow

Stratified flow is also referred to as the stratified smooth flow. In this flow regime, liquid flows along the bottom of the tube. The gas-liquid interface is relatively smooth. This pattern occurs at very low liquid and vapour velocities.

Stratified Wavy (Wavy Flow)

As the vapour velocity increases, the interface of the stratified flow becomes disturbed by waves travelling in the direction of flow. The gas-liquid interface is wavy and thus the term 'wavy flow'.

Slug Flow

The waves at the interface may increase in magnitude due to further increase in the vapour velocity and finally touch the upper portion of the tube forming a complete liquid bridge. This type of flow regime is called the slug flow. The upper surface of

the tube behind the wave is wetted by a residual film which drains into the bulk of the liquid.

Annular Flow

Annular flow in horizontal tube is similar to that in vertical flow except that the liquid film is much thicker at the bottom of the tube than at the top. Also, the wavy structure is more pronounced at the bottom of the tube causing more liquid to be entrained into the vapour core and deposited near the top of the tube.

Each of the above mentioned flow regimes will affect the CHF mechanisms in both the vertical flow and the horizontal flow. The mechanisms of CHF will be discussed in the next section with some consideration of the influence of flow pattern.

2.2 CHF Mechanisms

The critical heat flux for horizontal flow may be significantly lower than that for vertical flow under otherwise identical flow conditions. Gravity, which tends to cause flow stratification in horizontal flow, is the main reason for the difference in horizontal and vertical CHF's. The mechanisms involved in each case are quite different except for flows with high mass velocities. An improved understanding of the mechanisms associated with critical heat flux will permit an improvement in current prediction methods and may lead to the development of devices and systems to avoid its occurrence in practical applications.

2.2.1 CHF Mechanisms in Vertical Flow

For vertical channel flows, CHF can occur in subcooled boiling, in the low quality region and in the annular flow regime. The most commonly postulated mechanisms (Hewitt, 1982) in subcooled and low quality regions are

1. Near-wall bubble crowding and vapour blanketing
2. Local overheating following micro-layer evaporation from a nucleation site

3. Burnout associated with vapour clot or slug formation.

Figure 4 illustrates schematically the near-wall bubble crowding and vapour blanketing mechanism. A 'bubble boundary layer' builds up on the heated surface and is ultimately thick enough to prevent liquid migration to the surface, thus causing high temperature build up at the wall. The concept of boundary-layer separation for the burnout phenomenon was proposed by Kutateladze and Leontiev (1966). Tong (1972) modified the boundary-layer separation theory by pointing out that the friction factor for a channel with a bubble boundary layer is much higher than that for a smooth tube because the liquid has to flow over a rougher surface represented by the bubble boundary layer. He was able to derive a reasonably accurate semi-empirical correlation.

The second type of mechanism is shown schematically in figure 5. When a bubble grows at a nucleation site, 'micro-layer evaporation' occurs under the growing bubble, resulting in a disk of dry surface. The wall temperature at this dry patch rises rapidly and the patch can not be rewetted subsequent to bubble departure. The continually rising temperature spreads over the surface, thus giving rise to the burnout phenomenon.

Fiori and Bergles (1970) observed that CHF was often associated with the formation of vapour slugs/clots. They postulated that burnout occurs as a result of the evaporation of a thin liquid layer under the vapour slugs or clots, the vapour volumes preventing access of subcooled liquid to the surface (see figure 6). CHF in vertical annuli which occurred by the vapour-clot mechanism was studied by Rogers et al. (1982). Mechanisms in the subcooled and low-quality regions are reviewed by Tong and Hewitt (1972) and Bergles (1977).

Dryout in annular flow is most commonly associated with the drying of the liquid film by progressive entrainment, droplet deposition and evaporation. Dryout occurs as a result of the integral effect of droplet mass transfer, liquid entrainment and evaporation along the channel. Figure 7 illustrates the dryout mechanism in vertical annular flow in tube. Other similar mechanisms of dryout in vertical annular flow were

discussed by Hewitt (1982) in more detail. A review of the CHF mechanisms on a uniformly heated surface was done by Katto (1986).

2.2.2 CHF Mechanisms in Horizontal flow

In horizontal channels, gravitational force acts on both the vapour phase and the liquid phase in the direction that is not parallel to the fluid stream, causing phase separation. In these circumstances, the mechanisms of burnout are much more complex than those for vertical flows.

For subcooled boiling, Merilo (1977) hypothesized that the migration of the lighter phase (bubbles) towards the top of the channel as a result of the transverse buoyancy force causes an uneven distribution of void. This maldistribution of void has a severe effect on heat transfer in general and CHF in particular.

The flow patterns for horizontal flow are different from those for vertical flow. Figure 8 shows schematically the transitions of flow patterns in horizontal flow. Intermittent dryout occurs in the low quality region where bubbles coalesce and form a continuous vapour cushion along the upper portion of the tube (Becker, 1971). As vaporization continues downstream, the increased stream velocity causes higher amplitude waves to form on the steam-water interface. The faster moving gas stream impinges on the waves and thus causes liquid to be entrained in the vapour core region. Some of the entrained liquid is being deposited onto the upper portion of the tube and finally, the water will again cover the full circumference of the tube and annular flow is established. The annular flow in horizontal channel is not axi-symmetric. The annular liquid film is much thinner at the tube top because of draining. Usually, the downstream dryout will occur at the top of the tube first.

Studies of CHF mechanisms in different quality regions in horizontal channels have been reviewed by Fisher et al. (1978). They have identified the CHF mechanisms in three different qualities regions:

1. Very low steam qualities
2. Low and intermediate steam qualities

3. High steam qualities.

At low steam qualities, bubbles that are produced at the wall could form ribbons of vapour along the upper surface of the channel under low flow conditions. These vapour ribbons act as barriers and inhibit the replenishment of liquid lost by draining and evaporation thus causing a premature occurrence of the CHF condition and a subsequent steep rise in the wall temperature.

The mechanisms of CHF at low and intermediate steam qualities are very different from those at very low steam qualities. For low and intermediate steam qualities, the flows in evaporating channels are characterized by alternating large splashing waves (surges) which carry the liquid to the upper surface of the channel. There is little or no droplet entrainment activities and thus no replenishment of the liquid film at the top of the channel. As a result, the liquid film at the upper surface is subjected to drainage and evaporation which will finally dryout if sufficient time is given before the next splashing wave touches the upper surface.

For high steam qualities, the flow patterns would most likely be annular. Figure 9 shows a horizontal annular flow in air and water, for typical liquid film and vapour velocities (Fisher et al., 1978). The annular liquid film at the top of the channel is thinner as a result of draining along the circumferential direction. At the bottom of the channel, larger amplitude waves give rise to a great deal of droplet entrainment into the vapour core. Little entrainment occurs at the top of the channel because here the liquid film is much smoother. When the heat flux reaches the critical value, the liquid film at the top of the channel will be completely evaporated and thus causing 'dryout'. More details of the CHF mechanisms in horizontal annular flow will be provided in section 5.6.

2.3 Prediction of CHF in Vertical Tube Flow

2.3.1 Analytical Model

Dryout in annular flow is the most likely form to occur in practical systems, where the channel lengths are commonly several meters long. This type of dryout occurs as a result of liquid removal from the film leading to film dryout. An analytical model for dryout is possible if the rate of entrainment and deposition of droplets can be postulated. With the known local heat flux, the rate of evaporation can be calculated. The rate of change of liquid film flow rate with distance along the channel can be obtained through the mass balance equation, thus giving

$$\frac{A}{p} \times \frac{dG_{LF}}{dz} = G_D - G_E - \frac{q}{h_{fg}} \quad (2.1)$$

where G_{LF} is the mass flux (averaged over the total cross-sectional channel area A) of that part of liquid flow which is in the film, z is the axial distance, p the channel periphery, G_D the rate of droplet deposition per unit channel surface area, G_E the rate of entrainment per unit channel surface area, q the local heat flux, and h_{fg} the latent heat. Equation (2.1) is for a steady state and it ignores the contribution to evaporation by other mechanisms such as liquid flashing as a result of the channel pressure gradient. More sophisticated expressions which take into account these factors were given by Whalley (1987).

A number of predictive methods have been proposed for the calculation of dryout in annular flow. The methods differ principally in their treatment of entrainment, deposition and evaporation processes and in the choice of boundary conditions. Perhaps, the most widely accepted model is that developed at Harwell (Whalley et al. 1974, 1975, 1978 and Hewitt and Hutchinson 1976). The Harwell model is rather general and superior to most empirical models. However, more work needs to be done in advancing understanding of entrainment and evaporation processes.

2.3.2 Empirical Correlations

Burnout mechanisms in vertical tubes are still not fully understood despite many years of intensive research. However, due to the great importance of burnout phenomena, many researchers have developed correlations for burnout. Some of them are quite successful but most of them are not. This is because most correlations were developed based on limited data sources and hence limited range of applications.

Most of the successful correlations have the general form of

$$q_c = \frac{A' + B'\Delta h_{sub}}{C' + L_h} \quad (2.2)$$

which was originally devised by Macbeth (1963). Δh_{sub} is the inlet subcooling, A' , B' and C' are related to the system parameters and L_h is the tube length. Two most widely accepted correlations are Bowring's correlation (1972) and Biasi's correlation (1967).

Bowring's Correlation

Bowring's correlation for CHF in vertical up flow in round tubes gives q_c (W/m^2) as follows:

$$q_c = \frac{A' + 0.25DG\Delta h_{sub}}{C' + L_h} \quad (2.3)$$

where D is the tube diameter (m), G is the mass flux ($kg/m^2.s$), Δh_{sub} is the inlet subcooling (J/kg). The tube length L_h is in meters. A' and C' are functions of G , D , pressure P (Pa), and latent heat h_{fg} (J/kg) as follows:

$$A' = \frac{2.317(0.25h_{fg}DG)F_1}{1.0 + 0.0143F_2D^{1/2}G}$$

$$C' = \frac{0.077F_3DG}{1.0 + 0.347F_4(G/1356)^n}$$

where n is given by

$$n = 2.0 - 0.5P_R$$

where P_R is the ratio of the system pressure to a pressure of 6.895 MPa (equivalent to a pressure of 1000 psia). Thus

$$P_R = \frac{P}{(6.895 \times 10^6)} \quad (2.4)$$

The functions F_1 to F_4 are also functions of P_R as follows:

For $P_R < 1$:

$$F_1 = \frac{P_R^{18.942} e^{20.8(1-P_R)} + 0.917}{1.917} \quad (2.5)$$

$$\frac{F_1}{F_2} = \frac{P_R^{1.316} e^{2.444(1-P_R)} + 0.309}{1.309} \quad (2.6)$$

$$F_3 = \frac{P_R^{17.023} e^{16.658(1-P_R)} + 0.667}{1.667} \quad (2.7)$$

$$\frac{F_4}{F_3} = P_R^{1.649} \quad (2.8)$$

For $P_R > 1$:

$$F_1 = P_R^{-0.368} e^{0.648(1-P_R)} \quad (2.9)$$

$$\frac{F_1}{F_2} = P_R^{-0.448} e^{0.245(1-P_R)} \quad (2.10)$$

$$F_3 = P_R^{0.219} \quad (2.11)$$

$$\frac{F_4}{F_3} = P_R^{1.649} \quad (2.12)$$

The ranges of parameters covered by Bowring's correlation are as follows:

Pressure: 0.2-19.0 MPa

Tube diameter: 2-45 mm

Tube length: 0.15-3.7 m

Mass flux: 136-18,600 kg/m².s

Bowring reported that for the 3792 experimental points used, the RMS error of the correlation is 7% and the 95% confidence level is $\pm 14\%$.

Biasi's Correlation

Biasi's correlation has the advantage of being continuous with respect to system pressure with apparently little or no loss of accuracy. His correlation gives $q_c(W/cm^2)$ as follows:

$$q_c = \frac{1.883 \times 10^3}{D^n G^{1/6}} \left[\frac{f(P)}{G^{1/6}} - X \right] \quad (2.13)$$

for the low quality region

$$q_c = \frac{3.78 \times 10^3 h(P)}{D^n G^{0.6}} (1 - X) \quad (2.14)$$

for the high quality region

where $n = 0.4$ for $D \geq 1cm$

$n = 0.6$ for $D < 1cm$

and $f(P) = 0.7249 + 0.099Pe^{-0.032P}$

$h(P) = -1.159 + 0.149Pe^{-0.019P} + \frac{8.99P}{10+P^2}$

This correlation is evaluated in c.g.s units with the valid ranges as follows:

$$0.3cm < D < 3.75cm$$

$$20cm < L_h < 600cm$$

$$2.7bar < P < 140bar$$

$$10g/cm^2.s < G < 600g/cm^2.s$$

$$\frac{1}{1+\rho_f/\rho_g} < X < 1$$

For values of G below $30g/cm^2.s$ equation (2.14) is used whereas for other values of G , the critical heat flux is given as the greater of the two values obtained by equations (2.13) and (2.14). Based on the 4500 data points examined, the RMS error for this correlation was 7.26% and the 88% confidence level is $\pm 10\%$.

Groeneveld and Snoek (1986) compared Biasi's and Bowring's correlations with the AECL tube CHF data bank (containing 10,000 CHF data points). The comparison shows Biasi's correlation to be more promising. However, Biasi's correlation has

significant shortcomings when compared to experimentally observed trends, e.g., increasing the flow always results in the decrease of CHF according to Biasi's correlation whereas the experimentally observed trend shows that CHF increases with an increase in mass velocity at low qualities. Biasi's correlation is not continuous with respect to quality which is another drawback and it can also predict negative CHF values. A correlations developed based on a particular set of experimental data points often result in a limited range of application and tends to lose the physical significance of the parameters involved in CHF mechanisms.

Since most empirical correlations and analytical models have a limited range of application, there exists a need for a general technique for predicting CHF in vertical tube flow.

2.3.3 Table Look-up Method

In 1977, the USSR Academy of Sciences produced a series of standard tables of critical heat flux. The CHF values are tabulated as a function of the local parameters G , X and P for an 8 mm diameter tube. For tube diameters other than 8 mm, the critical heat flux may be approximated by

$$q_c = q_{c,8mm}(8/D)^{1/2} \quad (2.15)$$

for $4 \leq D \leq 16mm$.

Similar work was continued at the University of Ottawa and Chalk River Nuclear Laboratories using a much larger data base (more than 15,000 tube CHF data). The completed table was published in 1986 (Groeneveld et al., 1986a). Groeneveld's table look-up method is valid over wide ranges of flow conditions. It is accurate, simple to use, and has the correct parametric and asymptotic trends. The CHF table for an 8 mm tube is shown in Table 1. CHF values for a tube having other than 8 mm diameter may be obtained from

$$q_c = q_{c,8mm}(8/D)^{1/3} \quad (2.16)$$

for $4 \leq D \leq 16\text{mm}$.

The CHF table is also valid for bundle geometries with the appropriate correction factor. Thermal entrance effect is also accounted for in a form of length correction factor. The details of those descriptions are omitted in this work. A comparison of various CHF correlations and Groeneveld's table look-up technique against tube CHF data was made at ESDU (1986) and the results are summarized in Table 2. Bowring/Ahmad method listed in Table 2 is a combination of Bowring's correlation with Ahmad's (1973) fluid to fluid modelling parameter. Allowing for the differences in physical properties by using the Ahmad's modelling parameter, CHF for non-aqueous fluids was predicted from Bowring's correlation. The results show that the table method is superior to the other methods.

2.4 Prediction of CHF in Horizontal Tube Flow

2.4.1 Analytical Model

Ishigai and Takagi (1970b) proposed a general theoretical analysis of burnout phenomena in horizontal annular flow. Their analysis involves the mass balance equation

$$\frac{\pi D^2}{4} \frac{dG_{LF}}{dz} = -(E_v + E_e + E_s - E_d)\pi D \quad (2.17)$$

where E_v is the evaporation rate due to heat addition, E_e the rate of droplets entrained by evaporating steam flow, E_s the rate of droplets released from the liquid film due to its instability and E_d the rate of droplet deposition onto the liquid film.

The evaporation rate E_v is evaluated as follows:

$$E_v = \frac{q}{h_{fg}} \quad (2.18)$$

E_e was assumed proportional to the average steam velocity generated by evaporation, E_s assumed proportional to the growing velocity of a crest of an unstable wave and E_d was assumed proportional to the radial velocity component v' of the turbulence and the droplets concentration in the gas core.

Their prediction agrees quite well with the experimental data from Ishigai (1970a) but tends to be inaccurate outside that particular range of tube diameters, flow rates and pressures. The calculation procedure for their method requires numerical integration and the appropriate choice of boundary conditions, which are usually not well defined. Their model is not suitable for a wide range of flow parameters.

2.4.2 Correlations

There are not too many ad hoc correlations for the predictions of CHF in horizontal tubes (Merilo, 1979, Wang and Su, 1980 and Yoshida et al., 1986). This is mainly because of the scarcity of horizontal CHF data.

Merilo's (1979) correlation is one of the more acceptable for the prediction of CHF in horizontal tubes. He used the method of compensated distortion in deriving the horizontal CHF modelling parameter,

$$\psi_H = Re[Z^3 Bo]^{-1.05} \left(\frac{\mu_f}{\mu_g} \right)^{6.41} \quad (2.19)$$

where

$$\begin{aligned} Re &= \frac{GD}{\mu_f} \\ Z &= \frac{\mu_f}{\sqrt{\sigma D \rho_f}} \\ Bo &= \frac{(\rho_f - \rho_g)gD^2}{\sigma} \end{aligned}$$

His correlation is in the form of

$$\begin{aligned} \frac{CHF}{GH_{fg}} &= f(L/D, X_{in}, \rho_f/\rho_g, \psi_H) \\ &= 575 Re_L^{-0.340} (Z^3 Bo)^{0.358} \left(\frac{\mu_f}{\mu_g} \right)^{-2.18} \left(\frac{L}{D} \right)^{-0.511} \left(\frac{\rho_f}{\rho_g} - 1 \right)^{1.27} \\ &\quad \cdot (1 - X_{in})^{1.64} \end{aligned} \quad (2.20)$$

It correlates 462 Freon-12 and 143 water data points with RMS error of 9.12 and 9.07% respectively. The range of experimental parameters for their data base is shown in Table 3.

Atkinson and Rogers (1982) have shown that Merilo's modelling parameter can be applied to more complex geometries such as the 37-element nuclear fuel bundles. By using Merilo's modelling parameter, Atkinson and Rogers tried two forms of CHF equation for the bundle geometry:

$$\frac{CHF}{GH_{fg}} = a_0(\rho_f/\rho_g)^{a_1}(1 - X_{in})^{a_2}\psi_H^{a_3} \quad (2.21)$$

and,

$$\frac{CHF}{GH_{fg}} = b_0\psi_H^{b_1}(\rho_f/\rho_g - 1)^{b_2} + m_0\psi_H^{m_1}(\rho_f/\rho_g - 1)^{m_2}X_{in} \quad (2.22)$$

Equation (2.21) correlates 62 water and 67 Freon-12 data points with an overall RMS error of 4.6% while equation (2.22) correlates the same set of data with an overall RMS error of 4.4%. The applicability of Merilo's modelling parameter to bundle geometries is also partially confirmed by Ahmad et al. (1982).

Despite the applicability of Merilo's modelling parameters to the bundle geometries, his CHF correlation for horizontal tubes (equation 2.20) has some limitations. Some of the water data listed in Appendix A were used to test his correlation. As expected, the data from Merilo (1977) and Robertson (1973) agree very well with the predicted values but for data outside the range of the parameters listed in Table 3, his correlation does not predict the CHF values satisfactorily. Table 4 summarizes the results of the comparison. Most of the large errors are associated with low pressure conditions although some large errors occur also at higher pressure (e.g. Kohler and Hein's data). The ranges of G , X and D for the various experimental data can be found in Table 6. Like any empirical correlation, Equation (2.20) should not be used outside the ranges of parameters specified in Table 3.

Since Equation (2.20) is empirical in nature and based on inlet conditions, it is not expected to be able to account for the possibility of having superheated steam at the exit. Table 5 shows the exit quality as calculated through the energy balance equation with the CHF value predicted from Merilo's correlation (for $P = 1\text{ MPa}$, $L/D = 200$). For inlet qualities ranging from -50% to 0%, a large portion of the exit quality calculated showed that the steam is superheated at the exit in which case the CHF should

be zero. Also, the horizontal CHF predicted is much higher than the corresponding vertical CHF value. It would only predict a zero value for horizontal CHF if $X_{in} = 1$ and thus had ignored the possibility of flow stratification at low flow and negative inlet quality.

The overall RMS error for Merilo's correlation is found to be 80% when compared to the water data listed in Appendix A (data from Ishigai et al., Rounthwaite and Lis and Strickland were not included in the comparison). So, Equation (2.20) is not generally applicable over a wide range of flow parameters. Incidentally, the Merilo's scaling parameters (equation 2.19) may still be valid for correlating horizontal CHF data in tubes provided the coefficients and exponents are adjusted. For example, Merilo's scaling parameter could be used to determine the onset of flow stratification.

Both the Yoshida et al., and Wang and Su methods predict the dryout quality. Wang and Su's Correlation is valid for water while the equation of Yoshida et al. is valid for Freon-22. The correlation of Wang and Su has a simple form of

$$X_{do} = 8.81q^{-1/8}G^{-1/4} \quad (2.23)$$

Equation (2.23) is only valid for the following range of parameters:

pressure 4.9 MPa
 heat flux 233 - 698 kW.m⁻²
 mass velocity 500 - 1100 kg.m⁻².s⁻¹

It predicts most of their experimental data within the deviation of 10%. However, it is limited to the above range of flow conditions only. Prediction outside the specified ranges is disastrous. Up to now, there is no correlation that is accurate and generally applicable.

2.4.3 Groeneveld's Method

To determine the CHF for horizontal flow, Groeneveld (1982) suggested that the CHF for vertical flow be multiplied by a correction factor K_g , i.e.,

$$CHF_{hor} = K_g \times CHF_{table} \quad (2.24)$$

where CHF_{table} is the critical heat flux value obtained from the table look-up method (Groeneveld et al., 1986a). When flow is fully stratified, the CHF for horizontal flow is zero and hence $K_6 = 0$. On the other hand, as mass velocities in horizontal flow are high, effects of tube orientation on CHF become insignificant and hence CHF_{hor} may be assumed equal to CHF for vertical flow (CHF_{ver}). The lower and higher mass flux thresholds (G_1 and G_2 respectively) can be calculated for any set of given flow conditions by using a modified flow regime map adapted from Taitel and Dukler (1976) (see figure 10). Curve DD' represents the transition criterion below which stratification is noticeable and curve A represents the transition criterion below which full stratification occurs. Taitel and Dukler's transition criteria will be discussed in detail in Chapter 5. The flow parameters required for the determination of the mass flux thresholds are the quality, X , pressure, P and tube diameter D .

For flow conditions between the two mass flux thresholds, K_6 varies and depends on the flow parameters G , X , P and D . A simplified expression for K_6 factor was suggested by Groeneveld et al. (1986a) which assumes a linear relationship between the K_6 factor and the mass flux. The expression is shown as follows,

$$K_6 = \frac{G - G_1}{G_2 - G_1} \quad (2.25)$$

where

G = given mass flux

G_1 = lower mass flux threshold where complete stratification occurs

G_2 = upper mass flux threshold corresponding to the onset of noticeable stratification.

This approach has the correct asymptotic trends at the two mass flux thresholds, i.e., when the flow is fully stratified ($G \leq G_1$), the CHF will be zero and when the mass velocity is high ($G \geq G_2$), the CHF for horizontal flow will be equal to that for vertical flow.

2.5 Present Approach

Taitel and Dukler's criterion for the onset of noticeable stratification is not sufficient for an accurate prediction of the CHF ratio though its generalized nature is worth considering. An investigation of other dimensionless parameters which might serve as a controlling parameter for CHF ratio was undertaken and some improvement in the CHF ratio prediction was observed. The strategy was to derive analytically a dimensionless parameter which carries the effects of turbulence, buoyancy and other interacting forces worth considering and has the correct parametric trends. The parameter is then tested against experimental data to derive a new correlation for the correction factor for horizontal CHF. The following sections outline the preparation steps necessary for the derivation of the new correlation. The approach is described in detail in Chapter 5.

Chapter 3

EXPERIMENTAL DATA.

3.1 Data Sources

Table 6 presents a list of the sources of experimental data that are used for this study. The references are listed according to the group of fluids. For each source of experimental data, the ranges of pressures, mass flow rates, qualities, diameters and heat fluxes are shown to provide a better understanding of the experimental conditions.

The data bank was arranged in groups according to inlet condition (when possible), pressure (P), internal tube diameter (D) and heated length (L_h). They are further arranged in subgroups according to the mass flux and quality. Within each group of results, the following measured and calculated quantities are tabulated.

- | | |
|----------------|--|
| 1) G | mass flux ($kg.m^{-2}.s^{-1}$) |
| 2) X_{cr} | local critical quality |
| 3) CHF_{hor} | critical heat flux for horizontal flow ($kW.m^{-2}$) |
| 4) CHF_{ver} | critical heat flux for vertical flow ($kW.m^{-2}$) |
| 5) CHFR | critical heat flux ratio, CHF_{hor}/CHF_{ver} |
| 6) I | data index for CHF_{ver} |
| | 1—experimental |
| | 2—table look-up method |

In the test of Rounthwaite (1968), dryout occurred twice. It first started at low

quality and ceased at a higher quality because the vapour velocity caused a change to annular flow. Later, the failure of annular flow caused dryout at the top of the tube to begin again. For these cases, two separate points are recorded (data of Rounthwaite, 1968). The final data bank is listed in Appendix A.

3.2 Parametric Trends of CHF

Parametric trends of horizontal CHF must be identified and analyzed. Any CHF prediction method developed must be able to predict those trends as well as the CHF itself. If CHF is assumed to be dependent on local conditions only, then there are four basic parameters that can affect the CHF. They are the local quality, mass flux, tube diameter and pressure. The effects of each of these parameters on CHF and CHF ratio will be discussed.

3.2.1 Dryout Quality

CHF has a distinct dependency on dryout quality. At lower dryout quality, the CHF is higher. However, we are interested in the effect of dryout quality on CHF ratio (CHF_{hor}/CHF_{ver}).

Merilo (1977) noted the effect of quality on the relative CHF performance of vertical and horizontal geometries. He observed that for qualities greater than 40%, the vertical and horizontal CHF curves converge for increasing quality, whereas at less than 40% quality, and higher mass flux, the curves diverge for increasing quality (refer to figure 11). However, it must be noted that this trend may be partially due to the different mass velocities at the high and low qualities. Most of the other experimenters only observed the trend of CHF with quality rather than CHF ratio with quality. Merilo's observation should be considered when one tries to derive a dimensionless parameter that controls the CHF ratio.

At higher qualities, the vapour velocity will be higher, which then causes more axial drag and turbulence and a reduced effect of gravitation on the phase distribution. The

greater influence of turbulence over the buoyancy effect means that the effect of tube orientation is less significant and thus the CHF ratio increases. For subcooled or low-quality boiling (before the onset of net vapour generation), the flow pattern for horizontal flow is very similar to that for vertical flow. This is because the mechanisms governing the CHF are very similar to those for vertical flow. Some of the subcooled data obtained by Becker (1971) shows that the CHF ratio is well below the value of 1 (figure 12). This fact can be explained by the existence of void in subcooled boiling. The amount of vapour present is significant enough to cause some stratification even though the thermodynamic quality is less than zero. Therefore, the actual quality (or the actual amount of void present) is the real factor in the stratification of the flow. Also, Becker's data were obtained at low pressures for which the density difference is high and thus stratification is more likely.

Before bubble departure occurs, the bubbles remain attached to the wall and therefore the flow pattern for horizontal flow is similar to that for vertical flow. The parametric trend is then that the CHF ratio starts at 1.0 initially for zero actual quality (or onset of nucleate boiling) and stays very close to 1.0 until at a certain point when bubbles start to detach from the wall. After bubble departure, gravitational forces start to take effect and cause stratification to occur in low quality flows. From that point on, the CHF ratio decreases sharply with quality until the quality is high enough to cause some turbulence, thus suppressing the stratification effect. Thereupon the CHF ratio increases with increasing dryout quality and may eventually approach 1.0 again. Figure 13 illustrates the variation of CHF with quality for both vertical and horizontal tube flows. It is clear from this figure that the CHF values for both vertical and horizontal flow are very similar in the subcooled and low quality regions (or the CHF ratio has a value close to 1.0). As the quality increases, the CHF for horizontal flow decreases more than CHF_{ver} because of void migration (CHF ratio decreases). Finally, at higher quality when annular flow occurs, void migration is suppressed because of higher G and the CHF for horizontal flow approaches that for vertical flow (CHF ratio approaches 1.0). It is important that the actual quality be used in the analysis of

stratification criteria. At high qualities, the thermodynamic quality is approximately equal to the actual quality.

3.2.2 Mass Velocity

As explained earlier, higher mass velocities will prevent stratification and induce more mixing between the liquid and vapour phases. Consequently, a more symmetrical flow distribution will result. Therefore, the CHF ratio increases with increasing mass velocity. Figure 14 shows the effects of mass velocity on CHF for horizontal flow. However, linear relationship does not seem to be a correct representation of CHF ratio variation with mass velocity. Studies to include the non-linear relationship will be discussed in the later sections. All experimenters agree that as mass velocity increases, the CHF ratio approaches 1.0 which means that the CHF for horizontal flow is close to the counterpart for vertical flow. It is always safe to say that the CHF ratio increases with mass velocity.

3.2.3 Tube Diameter

As the tube diameter increases, there is more tendency for stratification to occur because the liquid has to move through a larger distance before reaching the top part of the tube. Therefore, the CHF ratio decreases with an increase in tube diameter.

Becker (1971) and Robertson (1973) observed that for a larger diameter tube, dryout occurs at lower quality range and that a higher mass flux threshold (G_2) is required in order to avoid the separation of the phases. This implies that CHF ratio decreases with increase in tube diameter. Merilo (1979) also studied the effect of tube diameter on CHF for both vertical and horizontal flow. He found a similar relationship between tube diameter and CHF as those described by Becker and Robertson. Figure 15 shows the effect of diameter on horizontal CHF for typical flow conditions.

3.2.4 Pressure

Pressure has some effects on the CHF ratio variation because it affects the buoyancy force acting on the two phases. Also, the latent heat of vaporization changes with pressure thus causing a change in the amount of heat required to evaporate the liquid film (CHF). With an increase in pressure, the density difference decreases and the buoyancy force will become less pronounced. As a result, one should expect the CHF ratio to approach 1.0 at near-critical pressure. At the same time, the density ratio ρ_f/ρ_g decreases with increasing pressure and results in a lower mixture velocity. So, less turbulence occurs and stratification seems likely to happen.

Becker (1971) observed that for high heat fluxes and high mass velocities, where downstream dryout occurred, the dryout quality increases with increasing pressure. However, for low heat fluxes and low mass velocities, the dryout quality decreases with increasing pressure. For the former case where mass velocities are high, the latent heat of vaporization decreases with an increase of pressure and therefore more vapour will be generated (thus higher quality) causing a more turbulent environment which suppresses dryout. For the latter case, where heat fluxes are low, an increase in pressure decreases the vapour velocity which decreases the mixing between the phases and causing a vapour cushion to exist at a higher mass velocity and at a lower steam quality. The effect of pressure on CHF is illustrated in figure 16.

3.2.5 Other Geometric Effects

Geometric effects such as bends in the piping just upstream of the test-section inlet can affect the phase distribution to a certain degree. The effects of bends on two-phase flow are not well understood at present. Robertson (1973) and Lis and Strickland (1970) had performed experiments with upstream bends and they found that the bend will generally tend to separate the two phases very effectively. The heavier liquid phase will collect on the outside surface of the bend and the lighter gaseous phase on the inside. The stratification effect might be suppressed or enhanced depending on

the direction of the bend. Spacers and flow obstructions also have some effects on the phase distribution. The two phases will be better mixed after passing through a spacer or flow obstruction. This is due to the generation of wakes or eddies downstream of the flow obstruction which in turn causes more turbulence in the flow. Therefore, the CHF will be enhanced if the flow encounters spacers or similar type of flow obstructions.

Among other factors that might affect the CHF is the presence of a compressible volume upstream of the test section such as a two-phase inlet condition.

Chapter 4

EVALUATION OF THERMO- DYNAMIC AND TRANSPORT PROPERTIES AND THERMALHYDRAULIC PARAMETERS

4.1 General

In this chapter, property codes for evaluation of fluid properties will be discussed. The property codes are capable of evaluating properties of water as well as those of non-aqueous fluids. Void fraction model, determination of actual quality and other preliminary background knowledge are reviewed and examined in this chapter.

4.2 Fluid Properties Evaluation

In all thermalhydraulic analysis, particularly in two-phase flow heat transfer, fluid properties must be known. The most common fluid media used in nuclear reactors

and commercial heat exchangers are water and refrigerants. It is important to predict accurately the thermodynamic and transport properties of these fluids. Many correlations and property prediction packages have been developed for light water and very few for heavy water. Most of them are commercial packages and proprietary software. A simple and accurate water property prediction software (UOCODE) has been developed by Cheng et al. (1987) at the University of Ottawa.

For non-aqueous fluids, no general method is available in the published literature. As a part of this thesis, a study to develop a general predictive method for property evaluation for non-aqueous, non-polar fluids was undertaken and completed. A semi-analytical predictive method was developed for non-polar fluids including the refrigerant family and methane family.

4.2.1 Properties for Water

The UOCODE developed by Cheng et al. (1987) uses simple correlations for the evaluations of water properties. It was developed for micro-computer applications. The required input parameters are the pressure and temperature. Properties evaluated are the specific volume, density, enthalpy, specific heat, thermal conductivity, viscosity and surface tension and latent heat of vaporization at the given pressure.

The range of validity of the UOCODE essentially covers all thermodynamic states from the triple point to critical point of water, i.e

$$\begin{aligned} 0.01^{\circ}\text{C} < T < 800^{\circ}\text{C} \\ 0.6113\text{kPa} < P < 22.09\text{MPa} \end{aligned}$$

The authors reported a root mean square error of less than 3% for all properties except at near critical condition. Recently, the UOCODE was updated to include the prediction of properties for heavy water and similar accuracy was reported.

4.2.2 Properties for Non-aqueous Fluids

A generalized property code was developed for the evaluation of thermodynamic and transport properties for non-aqueous fluids. This property code makes use of a four parameter equation of state developed by Adachi et al. (1983). Thermodynamic properties of the fluids were obtained through the derivatives of this equation of state while the transport properties were evaluated through the use of empirical correlations.

Equation of State

Adachi et al.'s equation of state was developed for non-polar substances and is thus valid for fluids such as Freons and light hydrocarbons. The equation of state is given by

$$P = \frac{RT}{V - b_1} - \frac{a(T)}{(V - b_2)(V + b_3)} \quad (4.1)$$

It is in cubic form with one temperature-dependent parameter $a(T)$ and three temperature-independent parameters b_1 , b_2 and b_3 . The parameters can be expressed as follows:

$$a(T) = \frac{AR^2T_c^2}{P_c} [1 + \alpha(1 - T_r^{1/2})]^2 \quad (4.2)$$

$$A = 0.44869 + 0.04024\omega + 0.01111\omega^2 - 0.00576\omega^3 \quad (4.3)$$

$$\alpha = 0.4070 + 1.3787\omega - 0.2933\omega^2 \quad (4.4)$$

and

$$b_i = \frac{B_i RT_c}{P_c}, i = 1, 2, 3 \quad (4.5)$$

where

$$B_1 = 0.08974 - 0.03452\omega + 0.00330\omega^2 \quad (4.6)$$

$$B_2 = 0.03686 + 0.00405\omega - 0.01073\omega^2 + 0.00157\omega^3 \quad (4.7)$$

$$B_3 = 0.15400 + 0.14122\omega - 0.00272\omega^2 - 0.00484\omega^3 \quad (4.8)$$

R is the universal gas constant, ω is the acentric factor of the substance which may be found from Reid et al. (1977) and T_r is the reduced temperature. This equation

of state is valid for gases and includes saturated liquid states. Derivations of thermodynamic properties from this equation are briefly discussed in the following sections. The equations used for the evaluation of each fluid property are presented in Appendix B together with the source code for the property code.

Specific Volume

With T and P as input parameters, the molar volume can be estimated using Newton-Raphson's iteration technique (with the equation of state). To obtain the specific volume, the molar volume is divided by the molecular weight of the fluid.

Enthalpy

Enthalpy is a relative quantity that has no absolute value and it is always evaluated with respect to a reference value. The relative enthalpy concept is shown in figure 17. If the enthalpy difference between two states P_1, T_1 and P_2, T_2 is desired, there are an infinite number of calculational paths, all of which give the same numerical results. Ideal gas heat capacity at zero pressure (C_p^0) for various gases are readily available. A convenient path of calculating the enthalpy difference is $AQCR$ in figure 17. Therefore, the enthalpy differences between two thermodynamic states using the path $AQCR$ can be expressed as

$$\begin{aligned} H_2 - H_1 &= (H^0 - H_{P_1})_{T_1} + \int_{T_1}^{T_2} C_p^0 dT - (H^0 - H_{P_2})_{T_2} \\ &= (H_{P_2} - H^0)_{T_2} - (H_{P_1} - H^0)_{T_1} + \int_{T_1}^{T_2} C_p^0 dT \end{aligned} \quad (4.9)$$

where

$(H_{P_2} - H^0)_{T_2}$ = Enthalpy departure function (it relates the enthalpy at P_2, T_2 to a reference state $P = 0$ at the same temperature)

If one chooses P_1 and T_1 to be the reference pressure and temperature at which the enthalpy is set equal to zero, then the enthalpy at any state P and T can be expressed

as

$$H = (H_P - H^0)_T - (H_{P_{ref}} - H^0)_{T_{ref}} + \int_{T_{ref}}^T C_P^0 dT \quad (4.10)$$

From the equation of state, the departure function can be derived as

$$\begin{aligned} \frac{(H - H^0)_T}{RT_c} &= (Z - 1)T_r + \frac{1}{B_2 + B_3} [A(T_r) - T_r \frac{dA(T_r)}{dT_r}] \ln \frac{Z - B_2 P_r / T_r}{Z + B_3 P_r / T_r} \\ \text{or} \\ (H - H^0)_T &= RT(Z - 1) + \frac{1}{b_2 + b_3} [a(T) - T \frac{da(T)}{dT}] \ln \frac{V - b_2}{V + b_3} \end{aligned} \quad (4.11)$$

where

$$A(T_r) = A[1 + \alpha(1 - T_r^{1/2})]^2 \quad (4.12)$$

The ideal gas specific heat at zero pressure for most substances can be expressed in terms of a third order polynomial function of temperature

$$C_P^0 = A + BT + CT^2 + DT^3 \quad (4.13)$$

The constants A , B , C and D are obtained experimentally and a list of substances with these constants is provided by Reid et al. (1977) and other engineering handbooks.

Specific Heat Capacity at Constant Pressure (C_P)

Specific heat capacity at constant pressure (or specific heat for short) is defined as the rate of change of enthalpy with respect to temperature at constant pressure. Therefore

$$C_P - C_P^0 = \left. \frac{\partial(H - H^0)}{\partial T} \right|_P \quad (4.14)$$

Differentiating equation (4.11) w.r.t T at constant P gives

$$\begin{aligned} C_P - C_P^0 &= - \frac{1}{b_2 + b_3} T \frac{d^2 a(T)}{dT^2} \ln \frac{V - b_2}{V + b_3} - R \\ &+ \left. \frac{\partial V}{\partial T} \right|_P \left[\frac{RT}{V - b_1} - T \frac{da(T)}{dT} \frac{1}{(V - b_2)(V + b_3)} \right] \end{aligned} \quad (4.15)$$

and

$$\left. \frac{\partial V}{\partial T} \right|_P = - \frac{(\partial P / \partial T)_V}{(\partial P / \partial V)_T} \quad (4.16)$$

$(\partial P/\partial T)_V$ and $(\partial P/\partial V)_T$ can be derived from the equation of state directly. Equation (4.16) is the famous Maxwell's Law.

Three other thermophysical properties (viscosity, thermal conductivity and surface tension) are also evaluated. The correlations used are discussed below.

Viscosity

Viscosity can be seen as a measure of the internal fluid friction which tends to oppose any dynamic change in the fluid motion. The mechanism or theory of gas viscosity has been reasonably well clarified by the application of kinetic theory of gases but not much is understood for the theory of liquid viscosity. This section outlines the viscosity estimation techniques for both non-polar gases and liquids.

Low-Pressure Gas Viscosity

For low-pressure gas viscosity estimation, either the kinetic theory or the law of corresponding states approach can be used. The theoretical method requires the knowledge of collision diameter and intermolecular potential function, which are not readily available, whereas the latter approach only requires the knowledge of the critical properties and molecular weight of the substance. The corresponding states approach is simpler to use and the constants can be easily found in the open literature. Both methods give approximately the same accuracy (Reid et al., 1977). Since the corresponding states approach is easier to use, it was chosen for the estimation of low pressure viscosity for non-polar gases. The exact equation used is the Thodos et al. equation (1970)

$$\mu^0 \xi = 4.610 T_r^{0.618} - 2.04 e^{-0.449 T_r} + 1.94 e^{-4.058 T_r} + 0.1 \quad (4.17)$$

where

$$\xi = T_c^{1/6} M^{-1/2} P_c^{-2/3}$$

T_c = Critical temperature, K

P_c = Critical pressure, atm

M = Molecular weight

μ^0 = Low-pressure gas viscosity, micro-poise

The expected error for this equation is normally between 1 and 3 percent for non-polar gases. It should not be used for hydrogen, helium, diatomic halogen gases and polar gases.

Dense-Gas Viscosity

For non-polar gases, the most accurate prediction method for dense gas viscosity yet suggested is the Jossi et al. (1962) equation

$$\begin{aligned} [(\mu - \mu^0)\xi + 1]^{0.25} = & 1.0230 + 0.23364\rho_r + 0.58533\rho_r^2 \\ & - 0.40758\rho_r^3 + 0.093324\rho_r^4 \end{aligned} \quad (4.18)$$

where ρ_r = reduced density

μ = dense-gas viscosity, micro-poise

The relation is valid for $0.1 \leq \rho_r \leq 3$. The exclusion of any specific temperature effect has been criticized by Rogers and Brickwedde (quoted by Reid et al., 1977). However, most ethane data reported by other researchers show no such temperature dependency. Despite its approximate nature, this correlation is reasonably accurate and simple to use. The agreement between experimental and estimated dense gas viscosities is reasonable. The error normally does not exceed 10 percent.

Liquid Viscosity

For estimation of saturated liquid viscosity (which is hereby referred to as liquid viscosity), group contribution methods are usually more accurate than corresponding states methods or other correlations. However, they are usually very complex and detailed chemistry of the substance must be known before any calculation can be made. A simple correlation for estimating low temperature liquid viscosity was suggested by Van Velzen et al. (1972). They assume that $\log \mu_L$ is linear in $\frac{1}{T}$. Their correlation is

shown as

$$\log \mu_L = B \left(\frac{1}{T} - \frac{1}{T^0} \right) \quad (4.19)$$

where μ_L = liquid viscosity, cP

T = temperature, K

B and T^0 are constants for each specific substance. A list of these constants for different substances was tabulated by Reid et al. (1977).

This relation is only valid for $T_r \leq 0.75$. For saturated liquid at higher temperatures, corresponding-states relations can be used. Letsou and Stiel (1973) suggested the correlation

$$\mu_L \xi = (\mu_L \xi)^{(0)} + (\mu_L \xi)^{(1)} \quad (4.20)$$

where

$$(\mu_L \xi)^{(0)} = 0.015174 - 0.02135T_r + 0.0075T_r^2 \quad (4.21)$$

$$(\mu_L \xi)^{(1)} = 0.042552 - 0.07674T_r + 0.0340T_r^2 \quad (4.22)$$

and μ_L is in centipoise and ξ is defined in the same way as before. This relation is only valid for $0.76 \leq T_r \leq 0.98$. Generally, an average error of about 3 percent was reported by the authors for T_r up to 0.92. Larger errors were found as the critical point was approached. Their method represents the best available for estimating saturated-liquid viscosities at temperature of $T_r \geq 0.76$.

Thermal Conductivity

Estimation of thermal conductivity for liquid or gas is similar to that of viscosity. Group contribution methods are generally the most accurate but not easy to apply because of the requirement of complex chemistry of the substance. The estimation of thermal conductivity is subdivided into three distinct thermodynamic regions, namely the low density gases, dense gases and liquid regions.

Low Density Gases Thermal conductivity

A simple and accurate method for the prediction of thermal conductivity for low density gases is the well-known Eucken correlation for polyatomic gases

$$\frac{\lambda^0 M}{\mu^0} = C_v + 4.47 \quad (4.23)$$

This simple Eucken relation is surprisingly good and usually more accurate than some other modified Eucken forms. Errors are usually less than 10 percent. Other correlations like the Roy-Thodos (1968,1970) and Bromley (1952) methods are very complex and they are only slightly more accurate than the simple Eucken form. Stiel and Thodos (1964) suggested a similar form to Eucken's equation and it generally predicts a slightly higher value than the Eucken form. For higher density gases, simple kinetic theory would not be sufficient to account for the interactive forces between the molecules.

Dense Gases Thermal conductivity

Stiel and Thodos suggested the following correlation for the dense gas thermal conductivity estimation.

$$\begin{aligned} (\lambda - \lambda^0) \Gamma Z_c^5 &= 14.0 \times 10^{-8} (e^{0.535 \rho_r} - 1) & \rho_r < 0.5 \\ (\lambda - \lambda^0) \Gamma Z_c^5 &= 13.1 \times 10^{-8} (e^{0.67 \rho_r} - 1.069) & 0.5 < \rho_r < 2.0 \\ (\lambda - \lambda^0) \Gamma Z_c^5 &= 2.976 \times 10^{-8} (e^{1.155 \rho_r} + 2.016) & 2.0 < \rho_r < 2.8 \end{aligned} \quad (4.24)$$

where $\Gamma = T_c^{1/6} M^{1/2} P_c^{-2/3}$ and Z_c is the critical compressibility factor of the substance.

This relation should not be used for polar substances or for hydrogen or helium. According to Reid et al. (1977), equation (4.24) appears to be the best generalized correlation.

Liquid Thermal conductivity

The thermal conductivity for liquid is quite different from that of gases. Reid et al. (1977) combined Sato's (1973) suggestion with Riedel's (1951) correlation and derived a new equation for thermal conductivity for a number of non-polar fluids in terms of

their respective normal boiling point. Their correlation has the following form

$$\lambda_L = \frac{2.64 \times 10^{-3}}{M} \left[\frac{3 + 20(1 - T_r)^{2/3}}{3 + 20(1 - T_{rb})^{2/3}} \right] \quad (4.25)$$

where T_{rb} is the normal boiling temperature. Thermal conductivity evaluated from equation (4.25) has a unit of $\text{cal.cm}^{-1}.\text{s}^{-1}.\text{K}^{-1}$. For $T_r > 0.8$ the equation for high density gas thermal conductivity (eq. 4.24) can be used.

Surface Tension

Brock and Bird (1955) suggested an equation for the surface tension evaluation and was later modified by Reid et al. (1977). The modified equation relates the surface tension to the normal boiling temperature of the substance. Their relation is given in equation (4.26)

$$\sigma = P_c^{2/3} T_c^{1/3} \theta (1 - T_r)^{11/9} \quad (4.26)$$

where $\theta = 0.1207 \left[\frac{1 + T_{rb} \ln P_c}{1 - T_{rb}} \right] - 0.281$

P_c is in atm. and T_c in Kelvin. Prediction from the above equation were compared with experimental data and the authors reported an average error of less than 5%.

Detailed description of the non-aqueous fluid property code is presented in Appendix B. The property code was tested against experimental data for a number of commonly-used fluids. Generally, very good agreement was obtained between the predicted and the experimental property values.

4.3 Determination of Thermalhydraulic Parameters

A number of thermalhydraulic parameters must be known before any analysis of stratification criteria can be made. Quality and void fraction are found commonly in most of the thermalhydraulic analyses. The onset of bubble departure is important in the determination of CHF relation between horizontal and vertical flows. Bubble sizes are also needed when calculating drag forces and turbulent forces on bubbles. The following sections briefly discuss the prediction methods for the above mentioned parameters.

4.3.1 Onset of Significant Void

Onset of significant void is sometimes known as the point of net vapour generation (figure 18). It is the point where the subcooling is low enough that bubbles grow and depart into the stream. Saha and Zuber (1974) proposed a correlation based upon the combined mechanisms of hydrodynamic criteria for bubble detachment and heat transfer restraint. The equilibrium quality at bubble departure was correlated as

$$X_{ed} = -0.0022 \frac{q_w D_{hy} C_{PL}}{\lambda_L h_{fg}} \quad \text{for} \quad Pe < 70000 \quad (4.27)$$

$$X_{ed} = -154 \frac{q_w}{G h_{fg}} \quad \text{for} \quad Pe > 70000 \quad (4.28)$$

where λ_L is the thermal conductivity of liquid, C_{PL} the specific heat of liquid and Pe is the Peclet number which is the product of Re_L and Pr_L . A large body of data was used by Saha and Zuber in deriving this correlation. The data base used includes water with

$$P = 0.1 - 13.8 \text{ MPa}$$

$$G = 95 - 2760 \text{ kg/m}^2 \cdot \text{s}$$

$$q_w = 0.28 - 1.89 \text{ MW/m}^2$$

in rectangular channels and annular and circular tubes. Data for Freon 114 were also used with

$$P = 0.32 - 0.85 \text{ MPa}$$

$$G = 101 - 2073 \text{ kg/m}^2 \cdot \text{s}$$

$$q_w = 0.0063 - 5.36 \text{ MW/m}^2$$

in an annular channel.

Their correlation was chosen for the present analysis because of its simplicity and the data base used in their derivation covers a wide range of flow parameters. However, a recent study by Rogers et al. (1987) have shown that Saha-Zuber's correlation does not apply at low flow ($G < 500 \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$) and low pressure ($P \approx 150 \text{ kPa}$) conditions.

4.3.2 Actual Quality

Usually, experimental data involving critical heat flux will contain information such as thermodynamic quality. In deriving criteria for stratification, actual quality is desired. For high quality regions, equilibrium quality X_e (or thermodynamic quality) is approximately equal to the actual quality but a similar argument can not be made in low quality or subcooled boiling regions. Estimation of actual quality is essential in low quality and subcooled boiling. Levy (1967) proposed a correlation for actual quality based on the onset of bubble departure. His equation is in the exponential form of

$$X = X_e - X_{ed} e^{X_e/X_{ed}-1} \quad (4.29)$$

where X_{ed} is the equilibrium quality at onset of bubble departure. Saha and Zuber (1974) suggested a similar equation in the form of

$$X = \frac{X_e - X_{ed} e^{X_e/X_{ed}-1}}{1 - X_{ed} e^{X_e/X_{ed}-1}} \quad (4.30)$$

Equations (4.27) and (4.28) can be used in the evaluation of the X_{ed} . Both equations (4.29) and (4.30) were developed based on vertical tube data and have a restriction that $X_{ed} \leq X_e$.

4.3.3 Void Fraction

In the analysis of the turbulent/buoyant force relation in two phase flow, the fraction of volume occupied by vapour in a cross section (or the void fraction, α) must be known. Void fraction is related to the quality in the following fashion

$$\frac{X}{1-X} = \frac{\alpha}{1-\alpha} S \frac{\rho_g}{\rho_f} \quad (4.31)$$

from which

$$\alpha = \frac{X}{X + S(1-X) \frac{\rho_g}{\rho_f}} \quad (4.32)$$

where S is the ratio of the average phase velocity of the vapour to that of the liquid. This velocity ratio is usually referred to as the slip ratio.

There are a number of correlations available for the estimation of slip ratio or void fraction. Some of the more successful correlations are those of CISE (Premoli et al. 1970), Chisholm (1983), Ahmad (1970) and some proprietary correlations.

Most void fraction correlations are actually correlations of the slip ratio, which is found experimentally to depend on parameters such as $\frac{\rho_f}{\rho_g}$, quality, mass flux and other minor variables such as tube diameter and inclination of the tube. Table 7 summarizes the dependence of slip ratio on these variables for some common correlations.

The performance of various correlations has been assessed in comparison with a wide range of data (Whalley, 1987). It was found that the most accurate generally applicable correlation is the CISE correlation. It has the following form

$$S = 1 + E_1 \left[\frac{Y}{1 + E_2 Y} - E_2 Y \right]^{1/2} \quad (4.33)$$

where

$$\begin{aligned} E_1 &= 1.578 Re^{-0.19} \left(\frac{\rho_f}{\rho_g} \right)^{0.22} \\ E_2 &= 0.0273 We Re^{-0.51} \left(\frac{\rho_f}{\rho_g} \right)^{-0.08} \\ We &= \frac{G^2 D}{\sigma \rho_f} \\ Re &= \frac{GD}{\mu_f} \\ Y &= \frac{\beta}{1 - \beta} \\ \beta &= \frac{\rho_f X}{\rho_f X + \rho_g (1 - X)} \end{aligned}$$

Equation (4.33) was essentially derived for vertical flow. It would not be expected to give good results at low velocities and pressures in vertical flows. The validity of the CISE correlation under subcooled condition has not been tested. Zuber and Findlay's (1965) equation for void fraction may be used for subcooled condition. Their equation has the form:

$$\alpha = \frac{X \rho_f}{C_0 [X \rho_f + (1 - X) \rho_g] + \rho_f \rho_g \frac{U_{au}}{G}} \quad (4.34)$$

where

$$C_0 = \beta \left[1 + \left(\frac{1 - \beta}{\beta} \right)^b \right]$$

$$b = \left(\frac{\rho_g}{\rho_f} \right)^{0.1}$$

$$U_{GV} = 2.9 \left[\frac{(\rho_f - \rho_g) \sigma g}{\rho_f^2} \right]^{0.25}$$

In summary, the recommended procedure for the calculation for void fraction is to calculate the actual quality from equation (4.30) and then use equations (4.32) and (4.33) for the bulk boiling condition and equation (4.34) for the subcooled condition.

4.3.4 Bubble size

Accurate prediction of bubble size has always been a difficult task. Bubble size is closely related to the bubble departure diameter. Ever since Fritz (1935) first proposed his correlation for bubble departure diameter, i.e.

$$d_D = 0.0208 \beta_0 \sqrt{\frac{g_c \sigma}{g(\rho_f - \rho_g)}} \quad (4.35)$$

where β_0 is the contact angle between the bubble and the wall surface, many other researchers have subsequently developed new correlations. Some are not very accurate while the others are too complicated. However, it must be noted that equation (4.35) is only valid for static conditions. For flow boiling, the mechanisms governing the bubble departure involves dynamic condition such as the drag force. The actual bubble departure size for flow boiling is much smaller than that for static conditions. It is not reasonable to assume that the average bubble size is the same as the bubble departure diameter.

Once the bubble is in the flowing stream, its size is determined by the balance of forces which are functions of the fluid properties and flow velocities. Average bubble size in the flowing stream can be related to the Weber number, defined as

$$We = \frac{\rho_g (u_g - u_f)^2 d}{\sigma} \quad (4.36)$$

At a certain critical Weber number, the bubbles will break up, thus resulting in a maximum diameter that a bubble can attain. By assuming the average size to be proportional to the critical Weber number, equation (4.36) can be rearranged to give

$$\begin{aligned} d &= \frac{We_{crit}\sigma}{\rho_g(u_g - u_f)^2} \\ &= Constant \times \frac{\sigma}{\rho_g(u_g - u_f)^2} \end{aligned} \quad (4.37)$$

Chapter 5

DERIVATION OF FLOW STRATIFICATION CRITERIA

5.1 General

It is important to know the parameters controlling the onset of flow stratification. Parameters and criteria proposed by previous authors are discussed in this chapter. In addition, new dimensionless parameters are derived based on a force balance and transit time ratio. These parameters can be used as measures of the degree of stratification. They have correct parametric trends with pressure, mass velocity, quality and tube diameter. In general, attempts are made to determine the ratio of the inertia force (or turbulent force) to gravitational force.

5.2 Taitel and Dukler's Transition Criteria

Taitel and Dukler suggested the transition criterion for flow regime transition from intermittent(slug or plug flow) to dispersed bubbly flow (curve D, figure 10). Their approach to this criterion is the balance of the radial turbulent force (the radial component of the pressure dynamic force due to the turbulence of water) with buoyancy force. Extension of this criterion to the annular flow regime (curve D' of figure 10) will

mean that above curve D', the annular flow in a horizontal tube is similar to that in a vertical tube. Therefore, the upper mass flux threshold (G_2) can be calculated from their criterion, i.e.

$$T^+ = \sqrt{\frac{8\tilde{A}_G}{\tilde{P}_i \tilde{U}_L^2 (\tilde{U}_L \tilde{D}_L)^{-0.2}}} = f_1(X) \quad (5.1)$$

where T^+ is

$$T^+ = \left[\frac{|(dP/dz)_{fs}|}{g(\rho_f - \rho_g)} \right]^{0.5} \quad (5.2)$$

and can be expressed as

$$T^+ = \sqrt{\frac{0.092 G_2^{1.8} (1-X)^{1.8} \mu_f^{0.2}}{g D^{1.2} \rho_f (\rho_f - \rho_g)}} = f_1(X) \quad (5.3)$$

where all the parameters in the first equation (with $\sim$) are defined according to Taitel and Dukler (1976) and are functions of Lockhart-Martinelli parameter only. Rearranging equation (5.1) gives

$$G_2 = \left[f_1(X)^2 \frac{g D^{1.2} \rho_f (\rho_f - \rho_g)}{0.092 (1-X)^{1.8} \mu_f^{0.2}} \right]^{0.556} \quad (5.4)$$

Similarly, the lower mass flux threshold, at which stratification occurs, can be obtained from the corresponding criterion

$$Fr^2 = \frac{G_1^2 X^2}{\rho_g (\rho_f - \rho_g) g D} = \frac{\tilde{C}_2 \tilde{A}_G}{\tilde{U}_G d \tilde{A}_L / \tilde{h}_L} = f_2(X) \quad (5.5)$$

which gives

$$G_1 = [f_2(X) \frac{\rho_g (\rho_f - \rho_g) g D}{X^2}]^{0.5} \quad (5.6)$$

Equations (5.4) and (5.6) define the upper and lower mass flux thresholds respectively and can be used for estimating the K_6 value as defined in equation (2.25). However, comparison of K_6 predicted from equation (2.25) against experimental CHF ratio (figure 19) has indicated that it underpredicts the CHF ratio. Modification to equation (2.25) is necessary for a more accurate prediction of K_6 .

5.3 Modified Froude Number

It is always possible to evaluate stratification effects of a two-phase flow in the horizontal tube through a dimensionless group, which has the inertia force of the steam in the numerator and the buoyancy force in the denominator. One such dimensionless group is the Froude number as defined by Taitel and Dukler in the horizontal flow regime map.

$$Fr = \frac{GX}{\sqrt{gD\rho_g(\rho_f - \rho_g)}} \quad (5.7)$$

The inertia force is approximately proportional to G^2X^2/ρ_g while the buoyancy force is incorporated in the $gD(\rho_f - \rho_g)$ term.

Figure 20 shows the effect of Fr on the difference in critical steam quality between the top (X_{cro}) and the bottom side (X_{cru}) of a horizontal tube (Kohler and Hein 1986). CHF occurs at the top first and as a result the critical steam quality at the top (X_{cro}) is smaller. When the mass velocities are high (higher Fr value), CHF occurs both at the top and at the bottom at the same time and so it can be assumed equal to that for vertical flow. It is evident from figure 20 that for Fr higher than 15, the tube orientation has no effect on the CHF. Therefore, this serves as a criterion for determining an upper mass flux threshold value ($G_{2,Fr}$)

$$G_{2,Fr} = \frac{15\sqrt{gD\rho_g(\rho_f - \rho_g)}}{X} \quad (5.8)$$

and then using non-linear mass flux interpolation,

$$K_6 = \left(\frac{G - G_1}{G_{2,Fr} - G_1} \right)^n \quad (5.9)$$

the K_6 value can be estimated.

5.4 Force Balance Approach

5.4.1 General

Before deriving the criterion for the onset of noticeable flow stratification, some important interacting forces must be considered. They are the buoyancy force, turbulent force and drag force. The forces involved for each flow regime are different from another flow regime. Basically, three distinct flow regimes are involved in non-stratified flows. They are the bubbly, droplet and annular flows. This section outlines the forces involved in each flow regime and attempts to derive a force balance equation based on parameters controlling flow stratification. Radial and axial transit time ratios for bubble and droplet trajectories will also be evaluated.

5.4.2 Governing Forces in various Flow regimes

Forces in Annular Flow

In Taitel and Dukler's analysis, the buoyancy force per unit length of the gas region is

$$F_B = g(\rho_f - \rho_g)A_G \quad (5.10)$$

and radial turbulent force per unit length is established to be

$$F_T = \frac{1}{2}\rho_f v'^2 p_i \quad (5.11)$$

where v' is the radial velocity fluctuation and p_i is the interface perimeter.

Forces in Bubbly Flow

The buoyancy force acting on each individual bubble can be expressed as

$$F_B = \frac{\pi d^3 g(\rho_f - \rho_g)}{6} \quad (5.12)$$

The drag force in the axial direction can be expressed as

$$F_D = \frac{1}{2}C_D \rho_f (u_g - u_f)^2 \pi d^2 / 4 \quad (5.13)$$

Pressure gradient that exists in the surrounding fluid in the axial direction is the major reason for the difference in the velocity difference. This pressure gradient is absent in the radial direction and thus the bubbles can be assumed to follow the turbulent fluctuations of the liquid in the radial direction. According to Levich (1962), the radial turbulent force is proportional to the square of the velocity fluctuation such that for bubbles

$$F_T = \frac{1}{2} \rho_g v'^2 \pi d^2 / 4 \quad (5.14)$$

where v' is the radial velocity fluctuation as mentioned earlier and d is the diameter of the bubble.

Forces in Droplet flow

The buoyancy force has a negative effect on droplets in the sense that it pulls the water droplets downward. The buoyancy force acting on an individual droplet can be expressed in a similar form to equation (5.12) except that for this case the diameter refers to the droplet diameter.

When liquid droplets are flowing in the pipe, drag forces exist between them and the moving vapour core. The drag force acting on each individual droplet is governed by

$$F_D = \frac{1}{2} C_D \rho_g (u_g - u_f)^2 \pi d^2 / 4 \quad (5.15)$$

For pre-CHF conditions, droplet flow occurs mainly in the core of the annular flow. It is not relevant to assume a radial turbulent force on droplets. Only the drag/buoyancy force ratio will be considered. However, it must be noted that droplets play an important role in annular flow and hence can affect CHF.

Other Forces

Some other important influencing factors involved in the stratification mechanism are the surface tension force and the viscosity effects. For small diameter tubes, liquids with contact angle $< 90^\circ$ (wetting liquids), have the tendency to climb the inner wall due to the capillary effect, thus forming a liquid film covering the complete inner

perimeter. The surface tension force can thus help in the prevention of stratification. An important parameter which represents the ratio of buoyant to surface tension forces is the Eotvos number. The viscosity number may be used as a measure of the viscosity effect.

The interacting forces can cause a variety of different flow patterns and it is important to relate these forces in a way that one can evaluate criteria for the onset of stratification. Some analytically and semi-analytically derived parameters are discussed in the following sections.

5.4.3 Force Balance in Annular Flow

Using an approach similar to Taitel and Dukler's (1986), the ratio of turbulent force to buoyancy force can be evaluated. Taitel and Dukler assumed the horizontal equilibrium interface perimeter, to be the boundary at which these two forces interact. In annular flow, the interface perimeter is much greater than the equilibrium interface perimeter, which is defined as the interface perimeter for smooth stratified flow (see figure 21). p_i for annular flow can be estimated as

$$p_i = \pi D_i \quad (5.16)$$

but

$$\frac{D_i^2}{D^2} = \frac{A_G}{A} \quad (5.17)$$

Therefore

$$D_i = D \sqrt{\frac{A_G}{A}} = D \alpha^{1/2}$$

Substituting D_i into equation (5.16) gives

$$p_i = \pi D \alpha^{1/2} \quad (5.18)$$

The root mean square value of v' is approximately equal to the friction velocity (Taitel and Dukler, 1986). Thus

$$(\bar{v'^2})^{1/2} = u^* = u_f \left(\frac{f_L}{2} \right)^{1/2} \quad (5.19)$$

Substituting equations (5.18) and (5.19) into (5.11) gives

$$F_T = \frac{1}{2} \pi \rho_f u_f^2 \left(\frac{f_L}{2} \right) D \alpha^{1/2} \quad (5.20)$$

Defining the parameter T_1 as

$$\begin{aligned} T_1 = \frac{F_T}{F_B} &= \frac{\frac{1}{2} \pi \rho_f u_f^2 D \alpha^{1/2} (f_L/2)}{g(\rho_f - \rho_g) A_G} \\ T_1 &= \frac{2 \rho_f u_f^2 (f_L/2)}{g D (\rho_f - \rho_g) \alpha^{1/2}} \end{aligned} \quad (5.21)$$

Assuming $f_L = 0.046 Re_L^{-0.2}$ for turbulent flow and substituting it into equation (5.21) yields

$$\begin{aligned} T_1 &= 0.046 Re_L^{-0.2} \left(\frac{1-X}{1-\alpha} \right)^2 \frac{G^2}{g D \rho_f (\rho_f - \rho_g) \alpha^{0.5}} \\ &= C_1 Re_L^{-0.2} \left(\frac{1-X}{1-\alpha} \right)^2 \frac{G^2}{g D \rho_f (\rho_f - \rho_g) \alpha^{0.5}} \end{aligned} \quad (5.22)$$

The parameter T_1 can be used as a measure of the dominance of the turbulent force over the buoyancy force. It has the correct parametric trends with G , X , D and P . Generally, it increases with G and X and decreases with D and P . The variation of this parameter with X and P are shown in figures 22a and 22b.

5.4.4 Force Balance in Bubbly Flow

The ratio of axial drag force to buoyancy force is useful in the analysis of stratification. This ratio is obtainable by dividing equation (5.13) by equation (5.12), thus giving

$$T_2 = \frac{3 C_D \rho_f (u_g - u_f)^2}{4 g d (\rho_f - \rho_g)} \quad (5.23)$$

The bubble diameter can be expressed in terms of Weber number and fluid properties. For a sphere with $10^3 < Re < 2 \times 10^5$ (Schlichting, 1968),

$$C_D \approx 0.5$$

where

$$Re = \frac{\rho_f (u_g - u_f) d}{\mu_f}$$

Also, bubbles will break up at a certain critical Weber number. Assuming break-up diameter to be the average bubble diameter, by substituting equation (4.37) into equation (5.23) and knowing that u_g and u_f can be calculated by $GX/\rho_g\alpha$ and $G(1-X)/\rho_f(1-\alpha)$ respectively, T_2 can be rearranged into the form of

$$T_2 = C_2 \left(\frac{\rho_g}{\rho_f} \right) \frac{G^4}{g\sigma\rho_f^2(\rho_f - \rho_g)} \left[\frac{\frac{\rho_L}{\rho_g}(1-\alpha)X - \alpha(1-X)}{\alpha(1-\alpha)} \right]^4 \quad (5.24)$$

where C_2 is an arbitrary constant.

The turbulent over buoyant force ratio for bubbly flow can be obtained in a manner similar to that for annular flow. Defining T_3 as the force ratio,

$$T_3 = \frac{F_T}{F_B} = \frac{\frac{1}{2}\rho_g v'^2 \pi d^2 / 4}{g(\rho_f - \rho_g) \pi d^3 / 6} \quad (5.25)$$

The root mean square value of v' is approximately equal to the friction velocity (Taitel and Dukler, 1986). Thus

$$(v'^2)^{1/2} = u^* = u_f (f_L/2)^{1/2} \quad (5.26)$$

Substituting v'^2 into equation (5.25) yields

$$T_3 = \frac{3 \rho_g u_f^2 (f_L/2)}{4 g d (\rho_f - \rho_g)} \quad (5.27)$$

Assuming $f_L = 0.046 Re_L^{-0.2}$ for turbulent flow and substituting it into equation (5.27) yields

$$T_3 = 0.0173 \left(\frac{\rho_g}{\rho_f} \right) \frac{\rho_f u_f^2 Re_L^{-0.2}}{g d (\rho_f - \rho_g)} \quad (5.28)$$

The bubble diameter may be approximated by using Weber number as described earlier, i.e., substituting equation (4.37) into equation (5.28) and rearranging yields

$$T_3 = C_3 Re_L^{-0.2} \rho_g^2 \frac{u_f^2 (u_g - u_f)^2}{g (\rho_f - \rho_g)} \quad (5.29)$$

where

$$u_g = \frac{GX}{\rho_g \alpha}$$

$$u_f = \frac{G(1-X)}{\rho_f (1-\alpha)}$$

Taitel and Dukler argued that when the buoyancy force is balanced by the radial turbulent force (i.e. when $T_3 = 1.0$), dispersion of bubbles starts to occur, at which point the flow distribution is more symmetrical. When T_3 is much greater than 1.0; the flow distribution for horizontal flow will be very similar to that for vertical flow under otherwise identical flow conditions.

5.4.5 Force Balance in Droplet Flow

In horizontal flow; the buoyancy force acting upon each droplet (of diameter d) is given by equation (5.12). The ratio of the drag force (equation 5.15) to the gravity force (same as equation 5.8) can be expressed as

$$T_4 = \frac{F_D}{F_B} = \frac{3}{4} C_D (u_g - u_f)^2 \frac{\rho_g}{g d (\rho_f - \rho_g)} \quad (5.30)$$

The droplet diameter can be related to Weber number, which is defined as

$$d = \frac{We_L \sigma}{\rho_f (u_g - u_f)^2} \quad (5.31)$$

Substituting equation (5.31) into equation (5.30) and simplifying yields

$$T_4 = \frac{3}{4} \frac{C_D}{We_L} (u_g - u_f)^4 \frac{\rho_g \rho_f}{g (\rho_f - \rho_g) \sigma} \quad (5.32)$$

The water droplets will break at a certain critical Weber number. Taking the average size of the droplets to be proportional to $\frac{\sigma}{\rho_f (u_g - u_f)^2}$, We_L can be treated as a constant. Since we are only interested in looking at the dominance of drag force over the buoyancy force, the constant terms in equation (5.32) can be combined to form an arbitrary constant and T_4 is redefined as

$$T_4 = C_4 (u_g - u_f)^4 \frac{\rho_g \rho_f}{g (\rho_f - \rho_g) \sigma} \quad (5.33)$$

By expressing the actual velocities in terms of mass flux, quality and void fraction, equation (5.33) is rewritten as

$$T_4 = C_4 \left(\frac{\rho_g}{\rho_f} \right) \frac{G^4}{g \sigma \rho_f^2 (\rho_f - \rho_g)} \left[\frac{\frac{\rho_f}{\rho_g} (1 - \alpha) X - \alpha (1 - X)}{\alpha (1 - \alpha)} \right]^4 \quad (5.34)$$

Equation (5.34) is exactly the same as equation (5.24) except for the constant C_4 . This parameter serves as a measure of the dominance of drag force over gravitational force. A criterion for onset of stratification based on this parameter should be investigated.

The approach taken here is very simplistic in nature. A more rigorous approach was suggested by Ishii (1977).

5.5 Transit Time Approach

5.5.1 General

An alternative to the force balance approach is to consider transit time for a bubble or droplet in both the vertical and the horizontal direction. The transit time taken for a droplet or bubble to travel across the channel is compared to the transit time to travel to the exit of the tube. This transit time ratio serves as a measure of void migration and hence a measure of the void accumulation near the top of the channel. Some simplified approaches were utilized in the development of the transit time ratio for various types of flow regimes such as droplet flow, bubbly flow and annular flow.

5.5.2 Bubbly Flow

For bubbly flow, the bubbles have an average velocity of

$$u_g = \frac{GX}{\rho_g \alpha} \quad (5.35)$$

Therefore the time taken for the bubble to travel to the exit is given by

$$t_x = \frac{L_h}{u_g} \quad (5.36)$$

or

$$t_x = \frac{\rho_g \alpha}{GX} L_h \quad (5.37)$$

By neglecting drag force in the vertical direction, the force balance in the vertical direction is

$$\frac{\pi d^3}{6} \rho_g \frac{du_y}{dt} = \frac{\pi d^3}{6} (\rho_f - \rho_g) g \quad (5.38)$$

where u_y = bubbly velocity upward.

Solving for u_y in equation (5.38) with zero initial velocity yields

$$u_y = \frac{(\rho_f - \rho_g) g t}{\rho_g} \quad (5.39)$$

Assume the average bubble starts to depart at the middle of the tube, the bubble rise time can be found by integrating the velocity w.r.t. time over the distance $D/2$, i.e.,

$$\frac{D}{2} = \int_0^{t_y} u_y dt \quad (5.40)$$

Substituting equation (5.39) into equation (5.40) and integrating gives

$$\begin{aligned} \frac{D}{2} &= \frac{1}{2} \frac{(\rho_f - \rho_g) g t_y^2}{\rho_g} \\ t_y^2 &= \frac{D \rho_g}{g(\rho_f - \rho_g)} \\ t_y &= \left[\frac{D \rho_g}{g(\rho_f - \rho_g)} \right]^{1/2} \end{aligned} \quad (5.41)$$

Therefore, the time ratio is defined as

$$T_s = \frac{t_y}{t_x} = \left[\frac{D \rho_g}{g(\rho_f - \rho_g)} \right]^{1/2} \frac{GX}{\rho_g \alpha L_h}$$

Rearranging gives

$$T_s = \frac{G}{\sqrt{g D \rho_g (\rho_f - \rho_g)}} \frac{X D}{\alpha L_h} \quad (5.42)$$

Equation (5.42) has the correct parametric trends for heated length, inertia force and buoyancy force.

5.5.3 Droplet Flow

One influencing parameter for onset of stratification is the ratio of the time taken for the droplet to fall down to the bottom of the tube over the time taken for the droplet to travel to the exit.

Assume a liquid droplet is flowing with a velocity u_f where

$$u_f = \frac{G(1-X)}{\rho_f(1-\alpha)} \quad (5.43)$$

Time taken for the droplet to travel to the end of the tube is given by

$$t_x = \frac{L_h}{u_f} \quad (5.44)$$

where L_h = tube length Substituting equation (5.43) into equation (5.44) gives

$$t_x = \frac{\rho_f(1-\alpha)}{G(1-X)} L_h \quad (5.45)$$

It is assumed that the droplets are entrained in the core of the tube and start to fall down to the bottom of the tube.

Neglecting drag force upwards, the force balance in the vertical direction is

$$\frac{\pi d^3}{6} \rho_f \frac{du_y}{dt} = \frac{\pi d^3}{6} (\rho_f - \rho_g) g \quad (5.46)$$

where u_y = droplet velocity downward

Solving for u_y in equation (5.46) with zero initial velocity yields

$$u_y = \frac{(\rho_f - \rho_g) g t}{\rho_f} \quad (5.47)$$

Similar treatment as in the bubbly flow can be performed to determine the time taken for the droplet to reach the bottom of the tube, i.e.

$$t_y = \left[\frac{D \rho_f}{g(\rho_f - \rho_g)} \right]^{1/2} \quad (5.48)$$

Therefore, the time ratio is defined as

$$T_b = \frac{t_y}{t_x} = \left[\frac{D \rho_f}{g(\rho_f - \rho_g)} \right]^{1/2} \frac{G(1-X)}{\rho_f(1-\alpha) L_h} \quad (5.49)$$

Rearranging gives

$$T_b = \frac{G}{\sqrt{g D \rho_f (\rho_f - \rho_g)}} \left(\frac{1-X}{1-\alpha} \right) \left(\frac{D}{L_h} \right) \quad (5.50)$$

The time ratio is important because the droplets formed might reach the bottom of the tube before exiting if the tube is long enough, thereby accumulating more liquid

at the bottom. Consequently less liquid is concentrated at the top of the tube and dryout can occur more easily.

It must be noted that the force balance and transit time ratio approaches are rather simplistic in nature. A more rigorous approach on the relative motion between the gas and liquid phases is given by Ishii (1977).

5.5.4 Annular Flow

Many researchers have investigated the mechanisms controlling the horizontal annular flow configuration. Recent studies include the works of Hutchinson et al. (1974), Laurinat et al. (1984) and T.F. Lin et al. (1985). Their works are discussed in more details in section 5.6. The transit time approach can not be easily used for annular flow because there is no discrete flowing particle for which the trajectory can be followed.

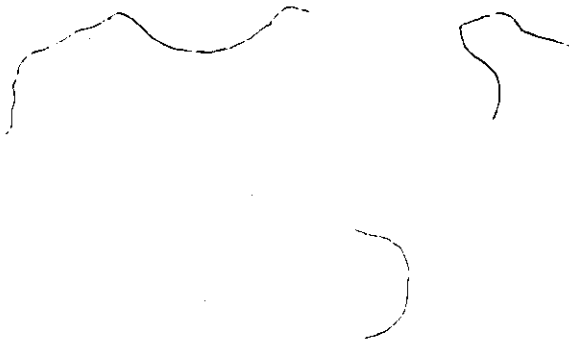
5.6 Annular Flow Distribution Approach

The asymmetrical distribution of the liquid film in horizontal annular flow is caused by the gravitational force. Hutchinson et al. (1974) proposed that there is a minor circumferential film flow from the top to the bottom of the pipe due to gravity. In order to maintain equilibrium, the liquid film near the top of the pipe had to be replenished by net droplet deposition, and the liquid film near the bottom had to be balanced by net droplet entrainment (Lin et al., 1986).

In addition to the droplet exchange model discussed above, Laurinat et al. (1984) recently proposed that there exists a secondary flow pattern in the gas core of a horizontal annular flow. In horizontal annular flows, the asymmetrical film distribution causes the interfacial roughness in the bottom of the pipe to be larger than that in the top. This rougher interface at the bottom presents more resistance to the gas flow in the axial direction and thus results in a circumferential (secondary) gas flow pattern as shown in figure 23.

Calculations of film thickness distribution were performed at Rensselaer Poly-

technic Institute (Lin et al.,1986), based on the combination of the two mechanisms discussed. The calculated results compare favorably with experimental data. This approach can be used for estimating critical heat flux by the inclusion of heat balance equations. However, this will add a considerable amount of complexity to the problem and further investigations have to be done.



Chapter 6

DERIVATION OF ORIENTATION CORRECTION FACTOR (K_6)

6.1 General

By combining two or more of the parameters developed in Chapter 5, a more complete and semi-empirical criterion for onset of stratification can be established. Several parameter groupings have been used in deriving an expression for the orientation correction factor K_6 . This chapter is devoted to the derivation of the K_6 expression. Three different approaches were examined and the present approach gives the best result. Comparison of prediction against experimental data was made and the errors are summarized in tabular form.

6.2 Groeneveld's Approach

Groeneveld (1982) suggested that the CHF for vertical flow be multiplied by a stratification factor K_6 to obtain CHF for horizontal flow, i.e.,

$$CHF_{hor} = K_6 \times CHF_{ver} \quad (6.1)$$

For stratified flow, $CHF_{hor} = 0$ and $K_6 = 0$. For a mass flux greater than G_2 obtained from equation (5.4), the horizontal CHF is approximately equal to the vertical CHF and hence $K_6 = 1.0$. For given mass flux that is between these two threshold values, K_6 factors can be approximated by

$$K_6 = \frac{G - G_1}{G_2 - G_1} \quad (6.2)$$

where G_1 is given by equation (5.6).

Comparison with data (figure 19) shows that equation (6.2) represents a lower bound to most of the data. Simple modification to include non-linear mass flux relationship can help improve the CHF_{hor} prediction. A form of

$$K_6 = \left[\frac{G - G_1}{G_2 - G_1} \right]^n \quad (6.3)$$

was suggested because it has correct parametric trends. With least squares best estimate curve fitting, n was found to have a value of approximately 0.62 and the root-mean-square error was found to be about 38.5% (error definition to be found in Section 6.5.1).

Figures 24 and 25 show the errors in prediction for linear and non-linear mass flux interpolation respectively. The non-linear approach gives a better prediction of CHF ratio. Both correlations give a large RMS error and this leads to the question of the reliability of curves A and DD' in figure 10.

Work has been done by Minato et al. (1986) to derive a new model for the transition mechanism from stratified gas-liquid flow into intermittent or annular flow. Their model incorporated the contribution of liquid kinematic energy to wave growth on the interphase surface. Minato et al. compared both the Taitel and Dukler's transition criterion and their model to their experimental data and concluded that Taitel and Dukler's criterion provides a prediction very similar to their own in spite of its neglecting of the water kinematic energy effect. Therefore it seems that Taitel and Dukler's transition criterion for G_1 is applicable.

When extrapolated to the annular flow regime, the criterion for the transition between intermittent flow and dispersed bubbly flow (curve D) may not be accurate

enough for the determination of G_2 due to the different mechanisms involved in the two-phase distribution. Also, the simplistic assumption represented by equation (6.3) may be another reason for the poor accuracy. Therefore, more accurate methods of estimating the G_2 value is required and such alternatives are discussed in the following sections.

6.3 Modified Froude Number Approach

Experimental water CHF values for horizontal flow were obtained from those listed in Appendix A and the ratio of horizontal CHF over vertical CHF was determined and plotted against Fr defined in equation (5.7). Figure 26a illustrate the trend of CHF ratio versus Fr . It can be concluded from this figure that the CHF ratio increases with Fr in general.

From an optimization technique using the least squares method, $Fr = 15$ was chosen as the criterion for the upper mass flux threshold, $G_{2,Fr}$. Prediction of K_6 based on this criterion and with the form of

$$K_6 = \left[\frac{G - G_1}{G_{2,Fr} - G_1} \right]^{0.6}$$

shows some improvement over Taitel and Dukler's approach. The root mean square error for this equation is about 30%. From the above analysis, it is evident that the Froude number contains important parameters affecting horizontal CHF. Perhaps the heated length over diameter ratio is equally important because a long heated tube will allow a small buoyancy effect to dominate. A longer tube means a longer time available for the bubble to rise to the top of the tube before exiting.

A further modification to the Froude number is possible by introducing the heated length. One such modification is to divide Fr by (L_h/D) ratio, defining

$$Fr^* = Fr \frac{D}{L_h} \quad (6.4)$$

where L_h = heated length.

A similar plot of CHF ratio vs. Fr^* (figure 26b) shows a similar trend as compared to figure 26a. There is still a considerable amount of scatter in the data. No clear-cut criterion for the upper mass flux threshold can be derived from this figure. Again, from the least squares curve fitting method, $Fr^* = 0.10$ was chosen as the upper bound at which the tube orientation has no significant effect on CHF and the G_2 value can then be calculated as³

$$G_{2,Fr^*} = 0.10 \left(\frac{L_h}{D} \right) \frac{\sqrt{g D \rho_g (\rho_f - \rho_g)}}{X} \quad (6.5)$$

With equation (6.5), the value of K_6 can be calculated for each given set of flow conditions by equation (6.3). For this approach, n was found to be about 0.60. Therefore,

$$K_6 = \left[\frac{G - G_1}{G_{2,Fr^*} - G_1} \right]^{0.60} \quad (6.6)$$

with G_1 defined in equation (5.6) and G_{2,Fr^*} defined in equation (6.5). The experimental CHF ratio was compared against the prediction defined in equation (6.6) (figure 27). Errors of prediction were shown in figure 28 and 29 against CHF ratio and quality respectively. This method provides a better prediction of CHF ratio as compared to the methods described in the preceding section. It is simple to use because of fewer calculation steps involved in evaluating G_{2,Fr^*} . The is found to RMS error is 29%.

6.4 Present Approach

6.4.1 Summary of Parametric Groups

The parameters derived in Chapter 5 have some similar basic groups. They are summarized in Table 8. The constants C_1 , C_2 , C_3 and C_4 are arbitrary constants to be determined by comparison with experimental data. All the parameters T_1 to T_6 have similar parametric trends in the sense that a larger parametric value means a smaller effect of stratification. The mass flux appears in the numerator of all parameters. This simply means that all parametric values increase with mass flux. Note that parameter T_5 is very similar to the modified Froude number except that void fraction appears in

the denominator of the former case.

Attempts will be made to relate the CHF ratio (CHF_{hor}/CHF_{ver}) to the parameters developed in Chapter 5. Different combinations of parameters or dimensionless groups are tested against experimental data to correlate a function for the CHF ratio. The details of the assessment technique are discussed in the following section.

6.4.2 Assessment Technique

It is known that for CHF experiments, the data obtained are accurate only within the precisions of the experimental set-up. Most of the experimental set-ups permit a measurement of CHF with an accuracy of $\pm 5\%$ (2σ confidence level). Due to the wide scatter of experimental data, it is not easy to find an optimum correlation considering the number of parameters involved. An assessment technique was developed for the determination of optimum correlation of parameters.

A crude approach is to plot the CHF ratio against each parameter and combinations of parameters. Figures 30-35 show some of the typical plots. From the plots, the parameter or combinations of parameter that give the clearest trend can be chosen and correlated. One drawback of this approach is that the combinations of the parameters are user defined and are not based on any theoretical deductions. A more scientific approach is developed for this purpose.

A statistical software package called SAS (Statistical Analysis System) was used to determine the correlation coefficient of each parameter with respect to the experimental CHF data. It was found that T_1 , T_3 and T_5 have a significant influence on the CHF ratio and they will be studied in more detail.

6.4.3 Derivation of CHF Correlation

From figures 30 to 35, CHF ratio seems to depend on the parameters in an exponential way. It approaches the value 1.0 as the parameter value becomes very large. Attempts were made to correlate the CHF ratio as some exponential function of the parameters

because an exponential function give the expected behaviour of the CHF ratio. One simple function the form of

$$CHFR = 1 - e^{-(T_i/A)^B} \quad (6.7)$$

was found to correlate the CHF ratio very well where T_i is one of the parameters shown in Table 8, A and B are the empirical constants corresponding to each T_i . Equation (6.7) can be rearranged to give

$$A = \frac{T_i}{[-\ln(1 - CHFR)]^{1/B}} \quad (6.8)$$

All six parameters were tested in the derivation of the correlation. All the arbitrary constants C_1 to C_6 were set equal to 1.0. For each parameter and B value, the horizontal CHF data bank was used to determine the value of A with equation (6.8). Unfortunately, due to the wide scatter of data, the value of A does not seem to be well defined. Attempts were made to determine a function for A but no suitable function was found. Figure 36 shows the values of A plotted against Martinelli's parameter for T_1 with $B = 0.5$. No systematic trend was found for A . Using the least squares fit, optimum values for A and B were obtained for each case which give the respective minimum RMS errors. Table 9 summarizes the error distributions for each parameter tested based on the constant local conditions. The comparison based constant inlet conditions is shown in Table 10. In both Tables 9 and 10, different values of A and B were tried with parameters T_1 , T_3 and T_5 . However, only the best correlated equations for parameters T_3 and T_5 were shown even though other constant values for A and B were investigated.

The best correlation appears to be with the use of parameter T_1 with $B = 0.5$ and $A = 65$. The use of different void correlations can affect the prediction of CHFR to some extent. Taitel and Dukler's void fraction correlation was tried without success. The CISE void correlation (see section 4.3.3) was chosen for this case because it is the most accurate generally applicable correlation (Whalley, 1987). However, the use of some proprietary correlations developed for horizontal tube flow may improve

the prediction significantly. With the CISE void correlation, the CHF ratio can be predicted by

$$CHFR = 1 - e^{-(T_1/65)^{0.5}} \quad (6.9)$$

where T_1 is defined in equation (5.22). Thus the CHF for horizontal flow can be predicted by

$$CHF_{hor} = CHFR \times CHF_{ver} \quad (6.10)$$

where CHF_{ver} is the CHF for vertical flow obtained from the Groeneveld look-up table. This correlation predicts the CHF ratio for water with reasonable accuracy (Tables 11 and 12) and is non-dimensional and hence may be applied to non-aqueous fluids such as refrigerants. Equations (6.9) and (6.10) were also used to predict the CHF for Freon-12 and compared to the data from Merilo and Ahmad (1979). The results are summarized in Tables 13 and 14. The parametric trends for equation (6.10) are discussed in the next section.

6.4.4 Parametric Trends of the CHF Correlation

To permit the development of a generalized correlation (applicable to a wide range of flow parameters), the correlation must have the correct asymptotic trends. Pressure, mass flux, tube diameter and quality are the four major flow parameters that affect the CHF. Parametric trends of equations (6.9) and (6.10) with respect to pressure, mass flux, tube diameter and quality are illustrated in figures 37 to 40.

Pressure has a direct influence on the density ratio, which is the main component of the buoyancy forces. The CHF ratio predicted from equation (6.9) is found to decrease with increasing pressure as would be expected from elementary considerations of the density ratio and the buoyancy forces. Increasing pressure results in the decrease of the density ratio ρ_f/ρ_g which in turn decreases the turbulent force as discussed in section 3.2.4. Figures 37a and 37b illustrate the pressure effects on the predicted CHF ratio.

The effects of mass flux on CHF ratio prediction at constant local conditions are

shown in figures 38a and 38b. Generally, the CHF ratio increases as the mass flux increases. This is in agreement with the experimentally observed trend. The quality used in the evaluation of CHF is the actual quality. For negative thermodynamic quality, Saha and Zuber's equation presented in Chapter 4 can be used to estimate the actual quality. Figures 39a and 39b show the trends of predicted CHF ratio with quality. At constant mass flux, pressure and tube diameter, the predicted CHF ratio increases with increasing quality except at low qualities ($X_{cr} < 0.01$) when the CHF ratio decreases with increasing quality. This predicted trend conforms to that discussed in section 3.2.1. As the actual quality approaches zero, the void fraction also approaches zero resulting in a very large value of T_1 (due to the term $\alpha^{-0.5}$) and therefore $CHFR \rightarrow 1.0$. The influence of tube diameter on CHF ratio was demonstrated in figure 40 based on constant local conditions. CHF ratio decreases with increasing tube diameter as expected based on the discussion in Section 3.2.3.

6.5 Comparison and Error Analysis

At the present, there is no accurate and generalized prediction method for the CHF in horizontal flow. Ishigai et al. (1970b) suggested an analytical model for horizontal annular flow but their method is very complex when heating is involved. Wang and Su (1980) have correlated their experimental data to give an ad hoc equation which is not valid outside their experimental range. Their method can not be used for comparison since the wrong parametric trends of their equation often give CHF values that are thousands of times greater than the data value (except for their own data). Merilo's (1979) correlation (eq. 2.20) seems to be the most promising and is compared with the present approach (Table 12).

The present method (equation (6.9)) is compared to experimental data from sources summarized in Table 6. Two methods of comparison were made: an error analysis based on constant dryout quality condition (local parameters) and an error analysis based on system parameter (constant inlet condition approach). Since Merilo's cor-

relation is based on the constant inlet conditions, it is only compared to the present approach with constant inlet conditions (Table 12). The prediction based on constant inlet condition is more accurate than that based on constant local parameters. These two types of predictions are discussed in detail in the following sections.

6.5.1 Constant Dryout Quality Condition

A Prediction based on constant dryout quality condition assumes that the CHF is a function of local parameters only. To make the comparison, CHF values are predicted directly from the equation or correlation using the local parameters given and then compared to the experimentally obtained values. The individual prediction error is defined as

$$Error_{pred} = \frac{CHF_{pred} - CHF_{expt}}{CHF_{expt}} \quad (6.11)$$

The mean error is the average value of all the individual prediction errors. The root mean square (RMS) error is defined as

$$RMS = \sqrt{\frac{\sum (Error_{pred})^2}{N}} \quad (6.12)$$

where N is the number of data points. The standard deviation is defined as

$$STD = \sqrt{\frac{\sum (Error_{pred} - Error_{mean})^2}{N}} \quad (6.13)$$

$Error_{mean}$ is the arithmetic mean of the overall errors, i.e.,

$$Error_{mean} = \frac{\sum Error_{pred}}{N} \quad (6.14)$$

again, N is the number of data points.

It is clear from Tables 11 and 12 that the present method is superior to the other methods.

6.5.2 Constant Inlet Quality Condition

Predictions based on constant inlet conditions require iteration. The principle behind this is to keep the inlet parameters (such as the inlet subcooling, ΔH_{in}) and the heated

length constant and vary the heat flux applied until CHF occurs. A prediction of CHF is made at the end of the tube corresponding to each heat flux value while keeping all the other parameters constant. At each step, the predicted CHF value is compared to the assumed heat flux value. Figure 41a shows schematically the iteration process. When the predicted CHF value is higher than the assumed heat flux, the quality at the end of the tube is increased (corresponding to an increase of assumed heat flux value) stepwise until the assumed heat flux has the same value as the predicted CHF. That final value (corresponding to the intersection of the two curves shown in figure 41a) will be the predicted CHF value used in the comparison.

Generally, the predictions based on constant inlet condition are more accurate than those based on local conditions. However, it is possible for low flow cases that predictions based on constant inlet condition give larger errors. In figure 41b, the slope of predicted CHF versus quality is positive for a range of quality. If the above iteration process is used, the final prediction will give a CHF value higher than that of the first prediction. This will give rise to a higher prediction error. Fortunately, in most industrial applications, critical heat flux occurs as a result of annular liquid film failure which corresponds to the downstream dryout for which CHF is decreasing with quality (negative slope).

Table 12 shows the error analysis for various prediction methods based on constant inlet conditions for water. Notice that predictions made from equation (6.3) improve significantly in this case when compared to the local parameters approach. On the contrary, equation (6.6) has become less accurate when constant inlet conditions are applied. Based on both the constant inlet and constant local parameters approach, it is concluded that equation (6.9) has a better overall prediction accuracy. The comparison for Freon-12 for the local parameters approach and constant inlet conditions approach are shown in Tables 13 and 14 respectively. Equation (6.3) predicts the CHF values more accurately for Freon-12.

Prediction errors for both water and Freon-12 data are also presented in figures 42 and 43. The applicability of equation (6.9) to non-aqueous fluids is partially confirmed

by the Freon data comparison even though the prediction was developed based on water data. This is because the dimensionless parameters were derived analytically based on fluid properties such as densities, viscosity and surface tension, regardless of the type of fluid involved. The errors quoted may seem very large to most people but in thermalhydraulic analysis of two-phase flows, errors of 20% are not uncommon.

6.5.3 Error Contribution Factors

There are a number of factors which can contribute to the rather large prediction errors. They are summarised below.

1. The CHF data sources are not very consistent even with similar experimental set-ups. Some of Merilo's data and those obtained from Kohler and Hein (1986) are from very similar experimental conditions, but the CHF values quoted by both groups are quite different from each other.
2. The CHF for vertical tubes is predicted from the Table look-up method which in itself has some errors involved. Data for vertical CHF under otherwise identical conditions to horizontal tubes are scarce due to the limitations of the experimental set-up. The table look-up method is the best so far for estimating vertical CHF values for a wide range of flow conditions.
3. In the low quality and subcooled boiling region, the equilibrium quality is very different from the actual quality. Saha and Zuber's equation (Equation 4.30), used for evaluating X_e has some weaknesses, especially under high pressure and high heat flux conditions, when it could predict an actual quality of more than 50% percent for negative equilibrium quality (see figure 44).
4. In deriving the dimensionless parameters based on the forces balance, some forces were neglected such as the surface tension force (in deriving T_1 , T_5 and T_6). Also, the

viscosity effects were not taken into account in deriving most of the parameters (except for T_1 and T_3 where μ was taken into account in the Reynolds number). These forces were neglected because they are believed to be insignificant. However, part of the inaccuracy in the predictions may be attributed to the exclusion of these forces.

Chapter 7

DISCUSSION AND CONCLUSIONS

CHF mechanisms for both the vertical and horizontal flow were reviewed and some available prediction methods were examined. The analysis presented here is somewhat simplified to avoid complex mathematical modelling. A better understanding of the forces involved in the flow mechanisms is needed before an improved prediction method can be developed. Experiments to study the void migration in a horizontal flow would be helpful in establishing the onset of stratification.

The scarcity of horizontal CHF data is also an area of concern. More experimental work on horizontal CHF should be done to provide a bigger data bank and to verify the validity of the present model. The model developed here has not been tested extensively. A better model can be developed if an extensive amount of horizontal CHF data is available. Experimental trends of CHF were discussed in terms of its variation with pressure, mass flux, quality and tube diameter. It was found that the horizontal CHF generally increases with mass flux and decreases with tube diameter. The effect of quality on horizontal CHF is somewhat more complicated. If the mass flux is low, the CHF first decreases with quality and then increases with quality and decreases with quality again at high quality region (see figure 13). The pressure effect on horizontal CHF was observed by Robertson (1973) and it was found that CHF

decreases with pressure. The predicted CHF was found to have the correct trend with pressure (figures 37a and 37b).

A generalized property code for non-aqueous fluids was also developed during the course of this research. This property code helps in the determination of fluid properties necessary for the prediction of CHF. Development of this property code was discussed in Chapter 4. More detailed discussion on the subroutines and comparison with experimental data can be found in Appendix B.

A generalized semi-analytical prediction method for CHF in horizontal flow has been developed. This prediction method is only valid for uniformly heated tubes and should not be applied to tubes with variable heat flux. It was tested against most of the horizontal tube CHF data available with different flow conditions. The root mean square error is about 16%. However, the correlation over-predicts CHF more than under-predicts it. It should be used with caution if a conservative prediction is required.

Under certain flow conditions (high pressure and high mass flux), equation (6.9) could under-predict the CHF_{hor} considerably. It is due to the slow approach of the exponential function towards the value of 1.0 even though the mass flux is supposed to be high enough to suppress the gravitational effect. Figure 44 shows the variation of CHF ratio with mass flux as predicted by equations (2.25) and (6.9). For mass flux greater than G_A , equation (2.25) predicts higher values of CHFR and thus converges towards the value of 1.0 sooner. If the maximum value of the two predictions is taken as the final predicted value, the problem of under-prediction would be solved. CHF_{hor} predicted from the proposed combination were compared to the water data and the results are summarized in Table 15. The results show an improvement for the prediction of horizontal CHF (RMS error of about 15%).

The method developed is also valid for non-aqueous fluids like Freons, nitrogen, carbon dioxide and other non-polar fluids. Groeneveld (1986c) suggested a few dimensionless groups for fluid to fluid modelling and his method has been found successful in predicting CHF for vertical flow for non-aqueous fluid using Groeneveld et al.'s CHF

table. For the prediction of CHF ratio, only the flow parameters and the fluid properties need to be known. The horizontal CHF for non-aqueous fluid can be predicted by using equation (6.9) in conjunction with Groeneveld's method of predicting CHF for vertical flow.

Both equations (6.3) and (6.9) represent two of the more generally applicable prediction methods which are valid for a wide range of flow parameters and for different fluids.

FINAL REMARKS AND RECOMMENDATIONS

1. The constant inlet conditions approach should be used when computing the CHF ratio if the inlet subcooling and the heated length are known. This approach is more accurate than the constant exit conditions (local parameters) approach. An iterative process is necessary if equation (6.9) is used, but it usually converges rapidly.
2. For qualities greater than 0.2, the equilibrium quality can be assumed equal to that of the actual quality. For subcooled and low quality flow boiling, the actual quality can be estimated from Saha and Zuber's equation (see section 4.3.2).
3. The mechanisms for horizontal CHF at low quality and subcooled boiling are not well understood at the present. Further experimental and analytical work for these flow conditions should be carried out before a more accurate and generalized prediction method can be developed.
4. Better predictions could result if the data were classified into different flow regimes (e.g. using the Taitel and Dukler's flow regime map) and attempts were made to correlate the data with different T_i in different flow regimes.
5. Experimental and analytical work is in progress at the Atomic Energy of Canada Limited (AECL) to study the void migration in a horizontal tube. The work is aimed at developing an analytical CHF prediction for horizontal flow.

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Table 1. Critical Heat Flux Lookup Table (kW.m^{-2}) [Groeneveld et al., 1986a]

PRESS. G		QUALITY																				
(KPA)	(KG/M.M.3)	-0.50	-0.40	-0.30	-0.20	0.15	-0.10	-0.05	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
100	0					3930	3630	2045	1200	1000	780	600	770	700	710	486	470	654	319	225	89	
100	50					4008	3500	2400	1700	1600	1500	1300	1250	1204	1126	879	850	800	501	355	350	
100	100					4800	4200	3100	2200	2100	2000	1850	1800	1800	1800	955	950	900	660	430	335	
100	200					5600	4900	3800	2600	2550	2500	1500	1400	1300	1246	1200	1124	1100	854	474	460	
100	300					6400	5600	4500	3000	3000	3000	2500	2400	2300	2300	2168	1721	1448	818	481	450	
100	400					7200	6300	5200	3600	3550	3500	3000	2900	2800	2758	2350	2101	1220	700	651	440	
100	500					8000	7000	5900	4200	4000	4700	4249	4006	3104	3081	2933	2407	1317	911	700	400	
100	750					8800	7600	6400	4800	4600	4600	3800	3600	3300	3300	3250	2503	1552	1100	600	100	
100	1000					9600	8200	7000	5500	4800	4800	4500	4551	4200	4000	3911	3105	2601	1100	600	100	
100	1500					10000	8800	7700	6000	5400	5300	5200	5100	5050	5000	4900	4549	2900	1100	600	100	
100	2000					10500	9400	8400	6500	6300	6000	5800	5700	5600	5500	5300	5200	3700	1100	600	100	
100	3000					11000	10000	9000	6900	6785	6450	6100	5900	5800	5700	5500	5400	4000	1000	600	100	
100	4000					11500	10600	9500	7300	7875	7400	7400	7200	7100	7000	6800	6700	5000	1000	600	100	
100	5000					12000	11500	11000	10300	9233	9000	8700	8500	8400	8300	8100	8000	6000	1000	600	100	
100	7500																					
150	0					6273	4000	3500	2400	1350	1200	1100	1000	950	930	913	588	550	344	315	250	116
150	50					6344	4100	3600	2700	1900	1800	1700	1500	1450	1416	1329	1002	900	873	519	419	400
150	100					6397	4800	4200	3200	2400	2200	2000	1900	1800	1800	1800	1093	1000	950	941	701	450
150	200					6488	5400	4800	3500	2700	2600	2500	2100	1600	1400	1200	1164	1150	1100	1000	1000	500
150	300					6571	6000	5400	4000	3000	2900	2800	2500	2400	1500	1400	1300	1200	1200	1200	1000	500
150	400					6721	6600	6000	4500	3700	3600	3500	3100	2700	1600	1500	1400	1200	1100	1000	670	450
150	500					7400	7200	6600	5000	4300	4150	4000	3500	2800	1400	1399	1300	1200	1100	1000	650	400
150	750					8000	7800	7200	5500	5200	4500	3985	3400	3200	1200	1105	1100	1100	1000	1000	600	150
150	1000					8600	8400	7600	6000	5500	4800	4250	3300	3100	2400	2000	1500	1300	1200	1100	550	100
150	1500					9200	9000	8200	6200	5700	4700	4300	4100	4000	3500	3000	2500	2000	1700	1500	550	100
150	2000					9800	9600	8240	5800	4800	4400	4300	4200	4100	3800	3300	3250	3200	2500	1000	500	100
150	3000					10200	10000	8636	6000	5000	4600	4500	4300	4200	3600	3000	2800	2600	2000	1000	450	100
150	4000					10700	10500	9900	9200	9145	7405	6500	5700	4000	3100	2800	2300	2000	1500	900	450	100
150	5000					11200	11000	10400	9700	9500	8881	8000	6500	5000	3000	2200	1800	1600	1000	600	400	100
150	7500																					
200	0					5971	4820	3700	2774	1450	277	262	248	233	219	204	175	146	117	87	58	29
200	50					6044	4955	4000	3094	2313	1794	1641	1562	1483	1405	1326	1244	1044	850	600	574	571
200	100					6099	5000	4100	3200	2603	2300	2100	2000	1900	1300	1200	1109	800	767	750	750	516
200	200					6193	5200	4300	3400	2800	2500	2300	2150	1400	1297	1200	1180	1100	1000	1000	1000	514
200	300					6278	5400	4450	3500	3000	2700	2400	2200	2150	2100	2000	1829	1497	904	417	400	150
200	400					6433	5600	4650	3700	3150	2900	2500	2400	2300	2250	2226	1759	1388	659	250	200	200
200	500					6610	5800	4850	3900	3300	3000	2650	2500	2314	2159	1818	1590	1463	1000	400	450	100
200	750					6775	6000	5000	4000	3400	3000	2600	2500	2134	1939	1800	1700	1600	1000	600	450	100
200	1000					7053	6200	5200	4200	3600	3000	2600	2500	2134	1939	1800	1700	1600	1000	600	450	100
200	1500					7370	6400	5400	4400	3800	3000	2600	2500	2134	1939	1800	1700	1600	1000	600	450	100
200	2000					7905	7000	5742	4800	4200	3000	2600	2500	2150	2050	1800	1700	1600	1000	600	450	100
200	3000					8600	8500	6411	5600	4500	3000	2600	2500	2150	2050	1800	1700	1600	1000	600	450	100
200	4000					8880	8607	6120	5267	4845	3000	2600	2500	2150	2050	1800	1700	1600	1000	600	450	100
200	5000					9990	6990	6465	5581	5077	3000	2600	2500	2150	2050	1800	1700	1600	1000	600	450	100
200	7500																					
300	0					5631	4650	3667	2683	1700	335	308	271	274	257	240	205	171	137	103	68	34
300	50					5712	5061	4292	3276	2975	2481	2327	2248	2168	2014	1860	1551	1067	935	500	500	450
300	100					5772	5200	4500	3500	3400	3200	3000	2900	2800	2600	2400	2160	900	870	850	800	504
300	200					5877	5600	4700	3600	3500	3200	2900	2800	2600	2400	2160	1400	1376	1100	1000	1181	569
300	300					5971	5592	4724	3300	3250	3200	2800	2700	2600	2500	2400	2176	1785	1043	418	400	162
300	400					6142	5634	4767	3300	3250	3200	2800	2700	2600	2500	2400	2176	1785	1043	418	400	162
300	500					6338	6000	5000	3900	3800	3200	2800	2700	2600	2500	2400	2176	1785	1043	418	400	162
300	750					6521	6200	5200	4000	4000	3200	2800	2700	2600	2500	2400	2176	1785	1043	418	400	162
300	1000					6862	6400	5154	4100	4000	3200	2800	2700	2600	2500	2400	2176	1785	1043	418	400	162
300	1500					7180	6600	5300	4200	4200	3200	2800	2700	2600	2500	2400	2176	1785	1043	418	400	162
300	2000					8000	7778	5670	4800	4768	3200	2800	2700	2600	2500	2400	2176	1785	1043	418	400	162
300	3000					8600	8441	6302	4918	4400	3200	2800	2700	2600	2500	2400	2176	1785	1043	418	400	162
300	4000					8852	8411	6051	4967	4525	3200	2800	2700	2600	2500	2400	2176	1785	1043	418	400	162
300	5000					10082	9816	6198	4236	4630	3200	2800	2700	2600	2500	2400	2176	1785	1043	418	400	162
300	7500																					
450	0					5363	4540	4222	2000	1948	180	360	340	320	300	280	246	200	160	150	120	110
450	50					5454	5035	4627	2330	2250	2195	2115	2035	1993	1950	1870	1860	1625	400	557	543	500
450	100					5522	5200	4100	3400	2900	2800	2700	2600	2550	2200	2000	1500	1123	1112	984	908	595
450	200					5639	5600	4150	3400	3000	2800	2600	2550	2500	2200	1700	1600	1500	1400	1106	879	595
450	300					5745	5145	2896	2850	2825	2800	2600	2500	2450	2400	2400	2300	2161	1583	755	447	608
450	400					5939	4187	2939	2900	2850	2800	2600	2400	2400	2300	2245</						

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Table 2. Comparison of CHF Data in Vertical Tubes with Various Correlations for All Fluids (ESDU, 1986).

CORRELATION	No. of Points	Mean Error*	Standard Deviation
(1) BOWRING (1972)			
Water data within his parameter ranges	3756	0.001	0.126
All water data	4579	0.155	0.155
(2) AHMAD (1973)			
Water data only	4579	0.381	0.350
All data	7861	0.265	0.324
(3) BOWRING/AHMAD			
All non-water data	3282	-0.003	0.193
Non-water, non-R.12 data	493	0.143	0.360
(4) KATTO and OHNO (1984)			
Restricted flow pattern	5364	0.011	0.144
All data	7861	0.003	0.140
(5) GROENEVELD et al. (1986a)			
Water data only	4304	0.044	0.098
All data	7287	0.064	0.112

* Mean Value of $\frac{\dot{q}_{cr,pred} - \dot{q}_{cr,expt}}{\dot{q}_{cr,expt}}$

Table 3. Range of Experimental Parameters used in Deriving Eq. (2.20)

Data	Fluid	Tube Diameter <i>mm</i>	<i>L/D</i>	ρ_f/ρ_g	Mass Flux <i>Mg/m²s</i>	<i>X_{in}</i> %
Merilo (1979)	Freon-12	12.6	193-387	13-20.5	0.7-5.4	-35 - 0
Merilo (1977)	Water	12.6	193-387	13-20.5	1.0-5.7	-30 - 0
Robertson (1973)	Water	19.1	112-160	20.5	0.7-1.4	-29 - -7
Merilo & Ahmad (1979)	Freon-12	5.3	193-571	13-20.5	1.6-8.1	-35 - 0

Table 4. Comparison of Merilo's (1979) Correlation with Water CHF Data

Data Sources	No. of Points	Average Error (%)	RMS Error (%)	Pressure Range (MPa)
Robertson (1979)	52	3.65	8.90	3.4 - 6.0
Leontiev et al. (1980)	23	-7.68	30.19	6.9 - 13.7
Becker (1971)	82	67.71	122.19	1.0 - 3.0
Merilo (1977)	34	-2.48	7.99	6.9 - 9.7
Kohler & Hein (1986)	69	55.80	81.36	10, 15, 20
Wang & Su (1980)	19	-68.16	69.33	4.9
All Data	279	28.8	80.3	

Table 5. Exit Quality Predicted by Merilo's (1979) Correlation

$$P = 1 \text{ MPa}$$

$$G = 2000 \text{ kg.m}^{-2}.\text{s}^{-1}$$

$$D = 0.01 \text{ m}$$

$$L/D = 200$$

$X_{in} (\%)$	CHF_{pred} (kW/m^2)	$X_{exit} (\%)$ (Calculated)
-50	9601	141
-45	9082	135
-40	8574	130
-35	8078	125
-30	7593	121
-25	7120	116
-20	6659	112
-15	6210	108
-10	5773	105
-5	5349	101
0	4938	98

Table 6. Sources of CHF Data for Horizontal Flow

Sources	Robertson*	Leontiev et al.	Becker	Merilo	Wang & Su
Fluids	water	water	water	water	water
Mass Flux ($kg.m^{-2}.s^{-1}$)	680- 1360	1000, 2000	160- 1742	950- 5700	300- 1100
X_{cr}	0.16-0.55	0-0.55	0-0.71	0.1-0.7	0.65-0.98
Pressure (MPa)	3.4-6.89	6.89- 13.73	1.0-3.2	6.89- 9.65	4.9
Diameter (mm)	12.7, 19.1	6.0	9.95, 12.9	12.6	12.0
Heated Length (m)	3.0	0.45	0.96	2.44, 3.66, 4.88	2.0
Heat Flux (kW/m^2)	200- 1500	800- 4450	750- 4020	500- 2500	116- 698
No. of Points	52	23	82	34	19

* Some of the measurements were obtained with a sharp bend in the pipe just upstream of the test-section inlet.

Table 6. (Cont'd)

Sources	Lis & Strickland**	Kohler & Hein	Rounthwaite	Ishigai et al.	Merilo & Ahmad
Fluids	water	water	water	water	Freon-12
Mass Flux ($kg.m^{-2}.s^{-1}$)	95-1100	500, 2500	94-214	95-800	1600-8100
X_{cr}	0.0-0.65	0.05-0.55	0.04-0.98	0.22-0.98	0.05-0.50
Pressure (MPa)	1.5-6.65	5, 10, 15, 20	1.48, 2.86	0.12-0.71	10.5, 15.2
Diameter (mm)	41.3	12.5, 24.3	41.3	5.6, 6.2, 9.95, 10.7, 15.3	5.3
Heated Length (m)	3.0	6.0	11.6	0.3, 0.5, 0.75, 1.0	1.03-3.05
Heat Flux (kW/m^2)	63	150-600	25-66	300-4300	43-353
No. of Points	21	69	12	131	203

** Measurements were obtained with a sharp bend in the pipe just upstream of the test-section inlet.

Table 7. Dependence of Slip Ratio S (Whalley, 1987)

Correlation	S depends on		
	ρ_f/ρ_g	X	G
Homogeneous model, $S = 1$	no	no	no
Zivi (1964)	yes	no	no
Chisholm (1972)	yes	yes	no
CISE (Premoli et al. 1970)	yes	yes	yes
Zuber et al. (1967)	yes	yes	yes
Bryce (1977)	yes	yes	yes
(steam-water only)			

Table 8. Summary of Dimensionless Parameters

Notation	Equation Form	
T_1	$C_1 Re_L^{-0.2} \left(\frac{1-X}{1-\alpha} \right)^2 \frac{G^2}{g D \rho_f (\rho_f - \rho_g) \alpha^{0.5}}$	(Eq. 5.22)
T_2	$C_2 \left(\frac{\rho_g}{\rho_f} \right) \frac{G^4}{g \sigma \rho_f^3 (\rho_f - \rho_g)} \left[\frac{\frac{\rho_f}{\rho_g} (1-\alpha) X - \alpha (1-X)}{\alpha (1-\alpha)} \right]^4$	(Eq. 5.24)
T_3	$C_3 Re_L^{-0.2} \rho_g^2 \frac{u_f^2 (u_g - u_f)^2}{g (\rho_f - \rho_g)}$	(Eq. 5.29)
T_4	$C_4 \left(\frac{\rho_g}{\rho_f} \right) \frac{G^4}{g \sigma \rho_f^3 (\rho_f - \rho_g)} \left[\frac{\frac{\rho_f}{\rho_g} (1-\alpha) X - \alpha (1-X)}{\alpha (1-\alpha)} \right]^4$	(Eq. 5.34)
T_5	$\frac{G}{\sqrt{g D \rho_g (\rho_f - \rho_g)}} \left(\frac{X}{\alpha} \right) \left(\frac{D}{L_h} \right)$	(Eq. 5.42)
T_6	$\frac{G}{\sqrt{g D \rho_f (\rho_f - \rho_g)}} \left(\frac{1-X}{1-\alpha} \right) \left(\frac{D}{L_h} \right)$	(Eq. 5.50)

T_1 - Turbulent/buoyant force	(Annular)
T_2 - Drag/Buoyant force	(Bubbly)
T_3 - Turbulent/Buoyant force	(Bubbly)
T_4 - Drag/Buoyant force	(Droplet)
T_5 - Transit time ratio	(Bubbly)
T_6 - Transit time ratio	(Droplet)

Table 9. Comparison of Horizontal Water CHF Data with Eq. (6.7) for Various Parameters and Constants for Local Parameters Approach

Equation	Mean ⁺ Error	RMS Error	Standard Deviation	Fraction of Data ⁺⁺ within prediction accuracy of		
				10%	20%	50%
$1 - e^{-(T_1/50)^{0.5}}$	0.033	0.281	0.279	0.2832	0.5484	0.9212
$1 - e^{-(T_1/55)^{0.5}}$	0.038	0.269	0.269	0.2545	0.5771	0.9212
$1 - e^{-(T_1/55)^{0.5}}$	0.038	0.269	0.269	0.2545	0.5771	0.9427
$1 - e^{-(T_1/65)^{0.5}}$	-0.048	0.256	0.252	0.2581	0.5305	0.9498
$1 - e^{-(T_1/70)^{0.5}}$	-0.069	0.255	0.245	0.2617	0.5233	0.9606
$1 - e^{-(T_3/20)^{0.5}}$	-0.002	0.471	0.471	0.2617	0.4480	0.6810
$1 - e^{-(T_3/0.06)^{0.9}}$	-0.065	0.267	0.259	0.3298	0.5448	0.9319
$1 - e^{-(T_3/0.065)^{0.8}}$	-0.066	0.264	0.255	0.3298	0.5914	0.9319

+ Mean of $\frac{CHF_{pred} - CHF_{expt}}{CHF_{expt}}$

++ No. of data point = 279

Table 10. Comparison of Horizontal Water CHF Data with Eq. (6.7) for Various Parameters and Constants for Constant Inlet Conditions

Equation	Mean ⁺ Error	RMS Error	Standard Deviation	Fraction of Data ⁺⁺ within prediction accuracy of		
				10%	20%	50%
$1 - e^{-(T_1/50)^{0.5}}$	0.027	0.169	0.167	0.4660	0.7133	1.0000
$1 - e^{-(T_1/55)^{0.5}}$	0.005	0.163	0.163	0.4444	0.7419	1.0000
$1 - e^{-(T_1/55)^{0.5}}$	-0.013	0.159	0.158	0.4050	0.7563	1.0000
$1 - e^{-(T_1/65)^{0.5}}$	-0.032	0.158	0.155	0.4229	0.7850	1.0000
$1 - e^{-(T_1/70)^{0.5}}$	-0.046	0.159	0.153	0.4229	0.7957	1.0000
$1 - e^{-(T_3/20)^{0.5}}$	-0.054	0.421	0.418	0.4353	0.5020	0.7412
$1 - e^{-(T_3/0.06)^{0.9}}$	-0.067	0.266	0.258	0.4029	0.6439	0.9281
$1 - e^{-(T_3/0.065)^{0.8}}$	-0.053	0.243	0.237	0.4532	0.6655	0.9496

⁺ Mean of $\frac{CHF_{pred} - CHF_{expt}}{CHF_{expt}}$

⁺⁺ No. of data point = 279

Table 11. Comparison of Horizontal Water CHF Data with Various
Correlations for Local Parameters Approach

Equation	Mean ⁺ Error	RMS Error	Standard Deviation	Fraction of Data ⁺⁺ within Prediction Accuracy of		
				10%	20%	50%
Eq. (6.2)	-0.329	0.438	0.288	0.1756	0.2975	0.6846
Eq. (6.3)	-0.007	0.390	0.390	0.2043	0.4265	0.8531
Eq. (6.6)	-0.018	0.292	0.292	0.2545	0.5305	0.8817
Eq. (6.9)	-0.048	0.256	0.252	0.2581	0.5305	0.9498
Wang & Su	Prediction is not valid due to the wrong parametric trend of the correlation					

+ Mean of $\frac{CHFR_{pred} - CHFR_{exp}}{CHFR_{exp}}$

++ No. of data point = 279

Table 12. Comparison of Horizontal Water CHF Data with Various
Correlations for Constant Inlet Conditions

Equation	Mean ⁺ Error	RMS Error	Standard Deviation	Fraction of Data ⁺⁺ within Prediction Accuracy of		
				10%	20%	50%
Eq. (6.2)	-0.224	0.304	0.206	0.2760	0.4695	0.8817
Eq. (6.3)	-0.023	0.162	0.161	0.3620	0.7885	1.0000
Eq. (6.6)	-0.115	0.424	0.408	0.4022	0.6052	0.8450
Eq. (6.9)	-0.032	0.158	0.155	0.4229	0.7850	1.0000
Merilo (1979)	0.288	0.803	0.620	0.3513	0.5627	0.7133
Wang & Su	Prediction is not valid due to the wrong parametric trend of the correlation					

+ Mean of $\frac{CHF_{pred} - CHF_{expt}}{CHF_{expt}}$

++ No. of data point = 279

Table 13. Comparison of Horizontal Freon-12 CHF Data with Various Correlations for Local Parameters Approach

Equation	Mean ⁺ Error	RMS Error	Standard Deviation	Fraction of Data ⁺⁺ within Prediction Accuracy of		
				10%	20%	50%
Eq. (6.2)	+0.173	0.265	0.201	0.2020	0.5271	0.9409
Eq. (6.3)	+0.153	0.252	0.201	0.1921	0.4975	0.9606
Eq. (6.6)	-0.283	0.367	0.232	0.1773	0.3251	0.7931
Eq. (6.9)	+0.111	0.264	0.239	0.1921	0.4877	0.9704
Wang & Su	Prediction is not valid due to the wrong parametric trend of the correlation					

⁺ Mean of $\frac{CHFR_{pred} - CHFR_{expt}}{CHFR_{expt}}$

⁺⁺ No. of data point = 203

Table 14. Comparison of Horizontal Freon-12 CHF Data with Various Correlations for Constant Inlet Condition Approach

Equation	Mean ⁺ Error	RMS Error	Standard Deviation	Fraction of Data ⁺⁺ within Prediction Accuracy of		
				10%	20%	50%
Eq. (6.2)	+0.102	0.148	0.107	0.4828	0.8473	1.0000
Eq. (6.3)	+0.097	0.175	0.111	0.4729	0.8473	1.0000
Eq. (6.6)	-0.566	0.727	0.455	0.1478	0.2414	0.4975
Eq. (6.9)	+0.086	0.172	0.149	0.3202	0.7833	1.0000
Wang & Su	Prediction is not valid due to the wrong parametric trend of the correlation					

+ Mean of $\frac{CHF_{pred} - CHF_{expt}}{CHF_{expt}}$

++ No. of data point = 203

Table 15. Comparison of Horizontal Water CHF Data with The
Combination Approach

Prediction Method	Mean ⁺ Error	RMS Error	Standard Deviation	Fraction of Data ⁺⁺ within Prediction Accuracy of		
				10%	20%	50%
<u>Constant X_{DO}</u>						
Maximum of Eq. (2.25) & (6.9)	-0.016	0.247	0.247	0.2760	0.5699	0.9498
Eq. (6.9) Alone	-0.048	0.256	0.252	0.2581	0.5305	0.9498
<u>Constant X_{in}</u>						
Maximum of Eq. (2.25) & (6.9)	-0.012	0.150	0.149	0.4660	0.8208	1.0000
Eq. (6.9) Alone	-0.032	0.158	0.155	0.4229	0.7850	1.0000

+ Mean of $\frac{CHF_{pred} - CHF_{exp}}{CHF_{exp}}$

++ No. of data point = 279

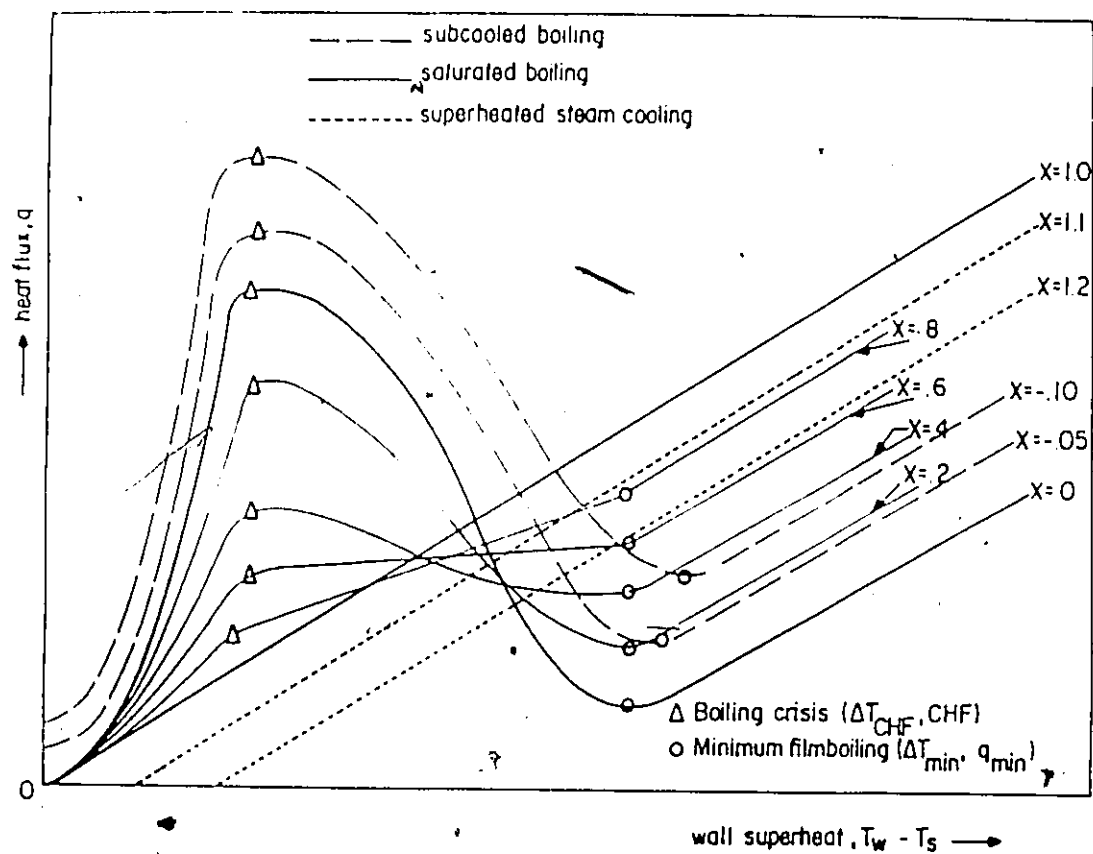


Figure 1. Typical Boiling Curve for Two Phase Flow.

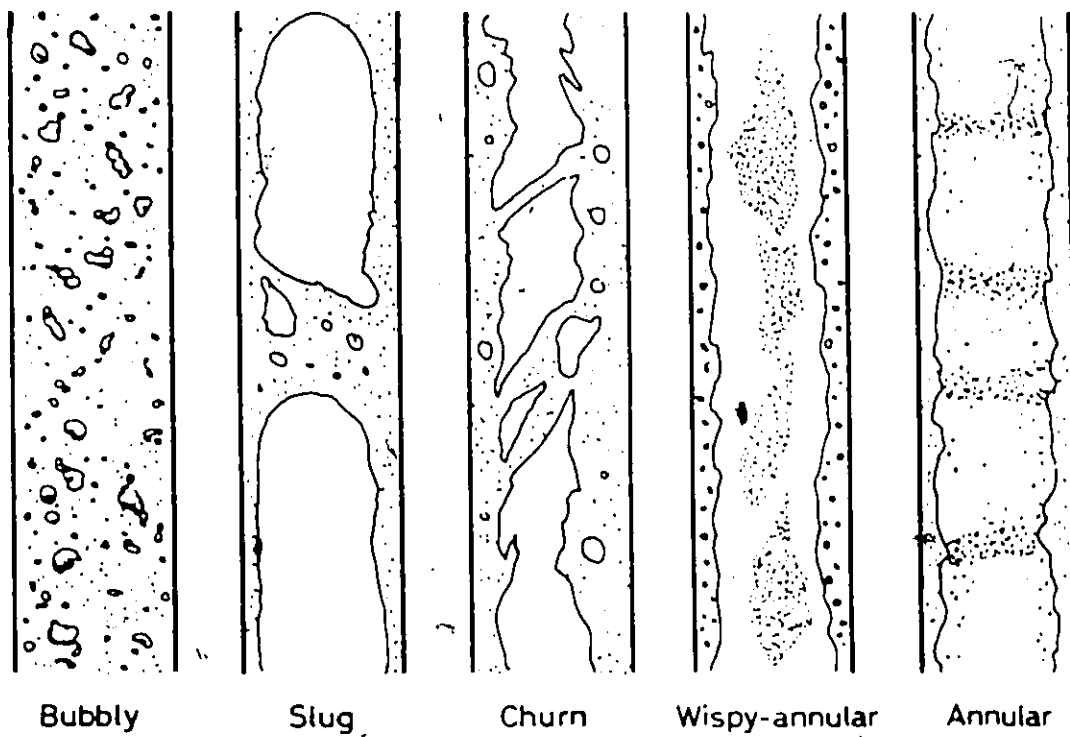


Figure 2. Flow Regimes for Vertical Flow.

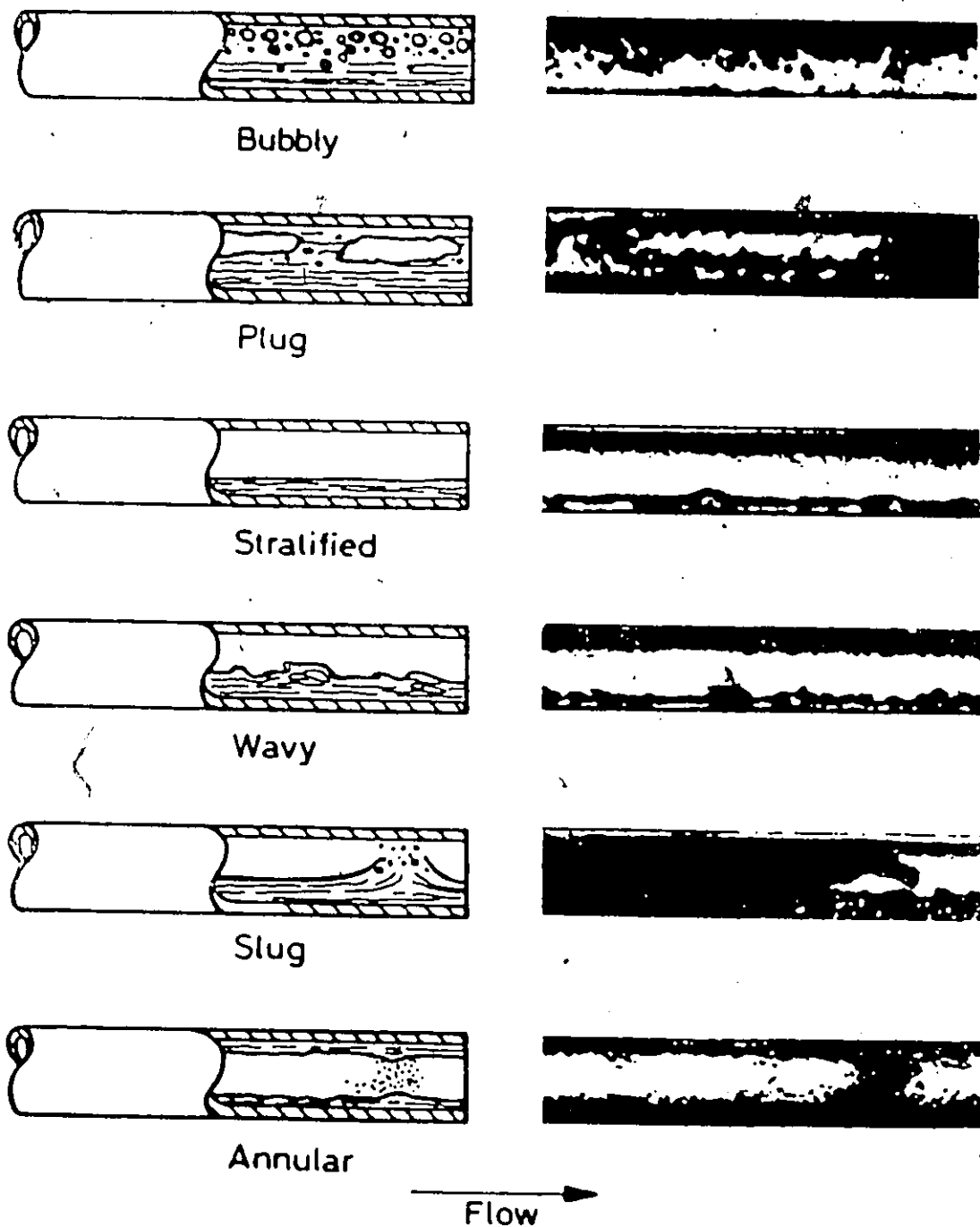


Figure 3. Flow Regimes for Horizontal Flow.

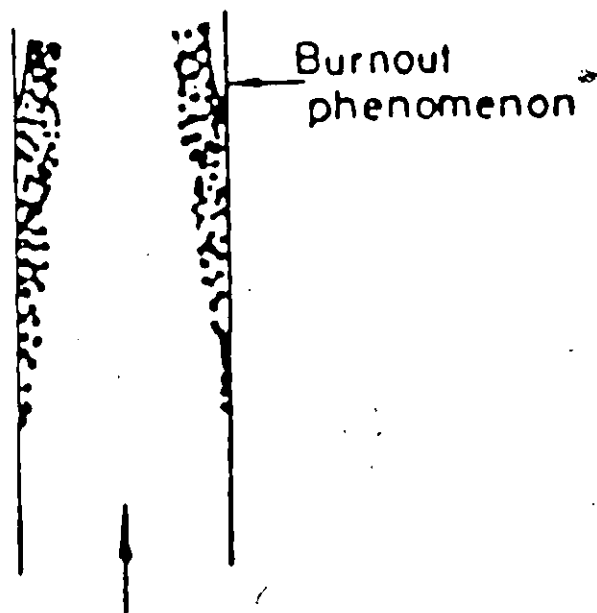


Figure 4. Near-wall Bubble Crowding and Vapor Blanketing Mechanism for Burnout Heat Flux in Subcooled and Low-quality Flows.

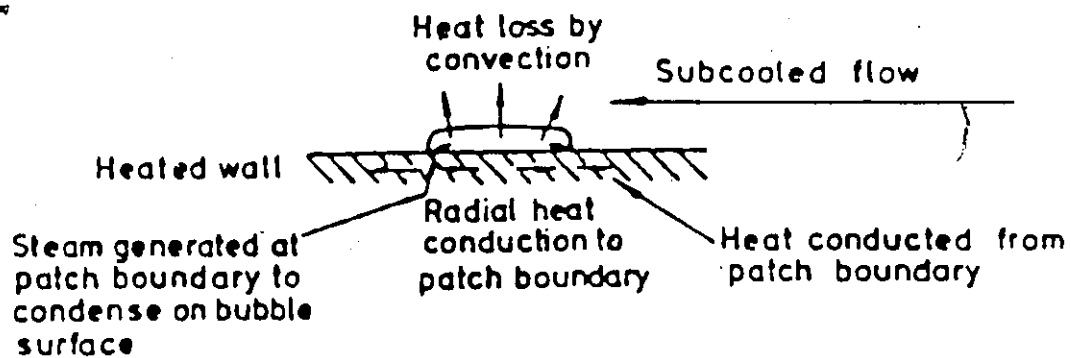


Figure 5. Local Overheating Following Bubble Growth from a Nucleation Center.

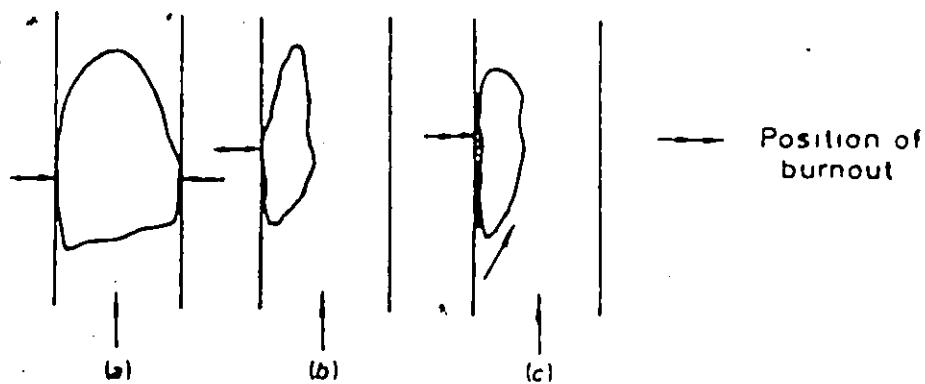


Figure 6. Burnout Associated with Vapor Clot or Slug Formation.

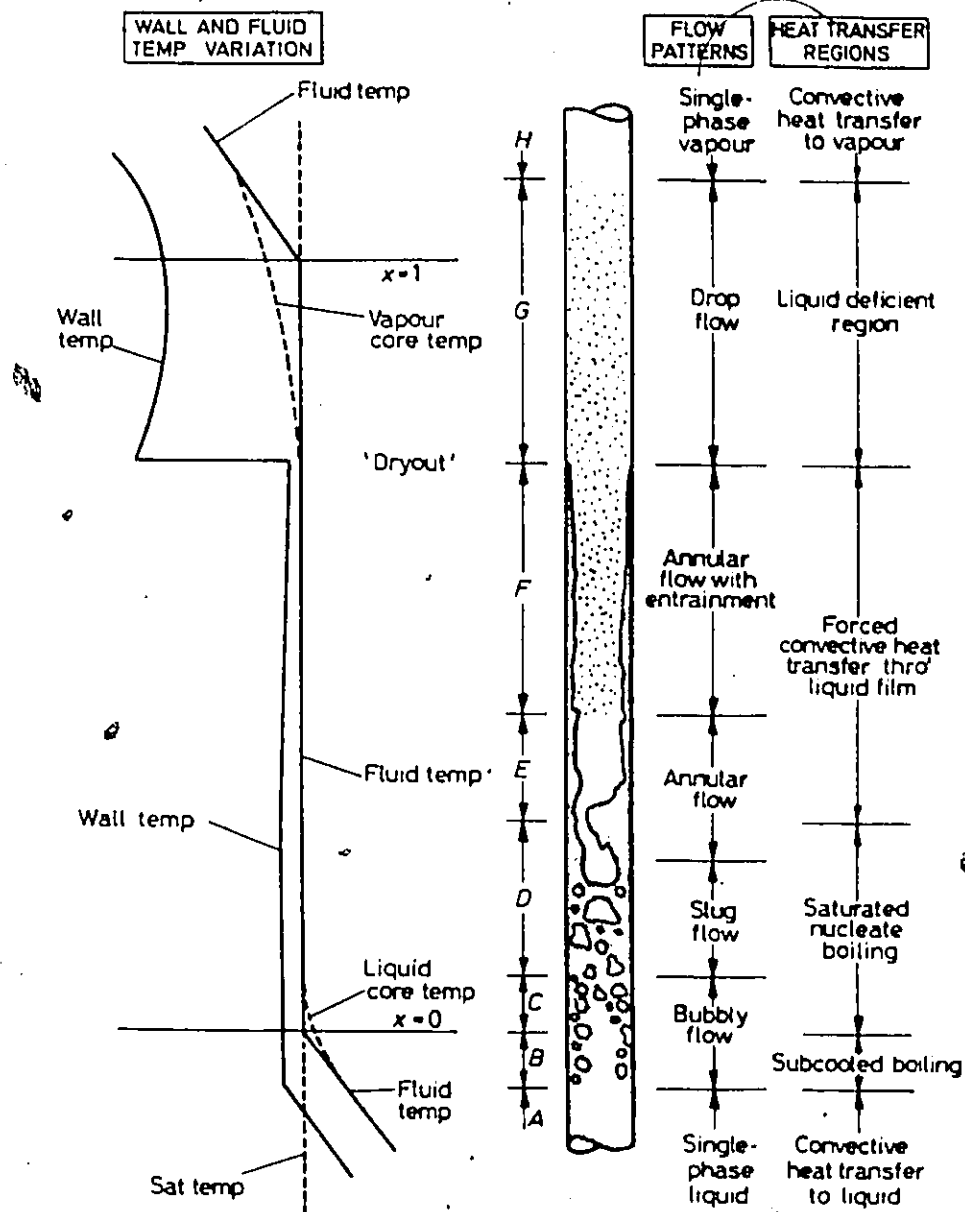


Figure 7. 'Dryout' in Vertical Tube Caused by Annular Liquid Film Failure (Collier, 1984).

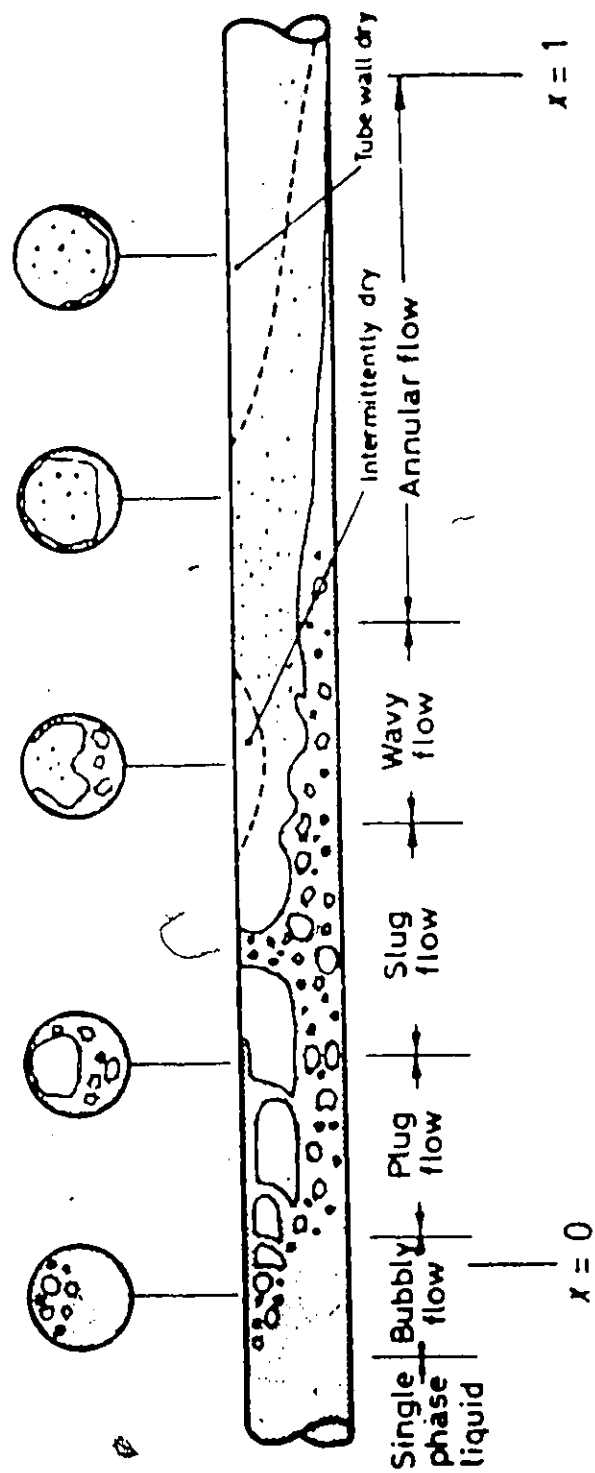
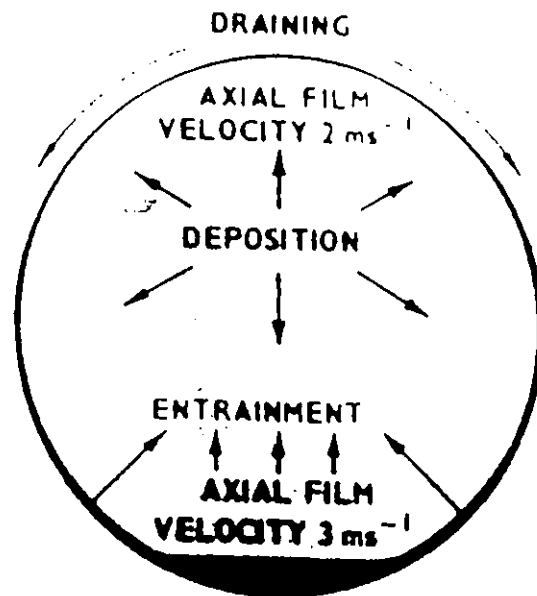


Figure 8. Flow Regimes for Horizontal Flow (Becker, 1971).



CORE VELOCITY 32 ms^{-1}

ENTRAINED FRACTION 50%

FILM THICKNESS
VARIES BETWEEN
0.15 mm AND 2 mm

Figure 9. Horizontal Annular Flow in Air and Water (Fisher, 1978).

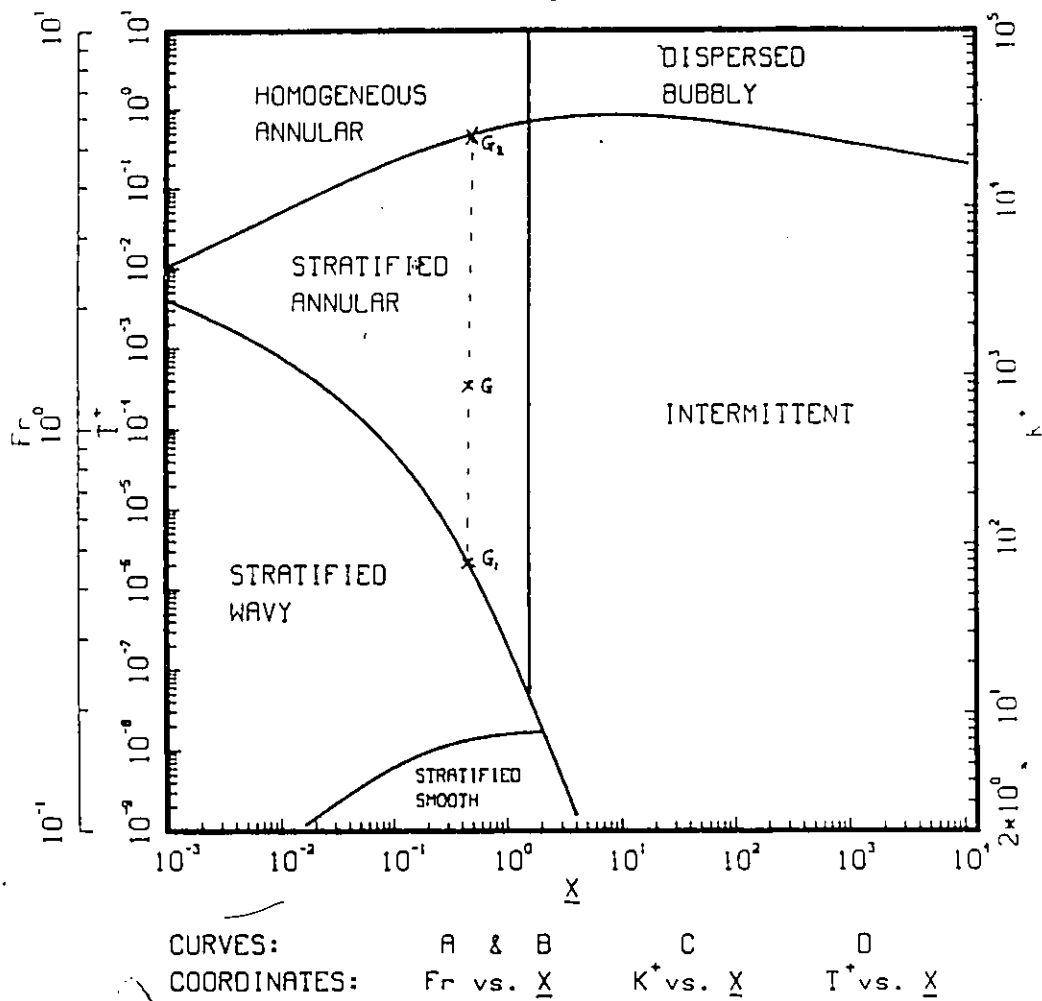


Figure 10. Modified Generalized Flow Regime Map for Horizontal Flow.

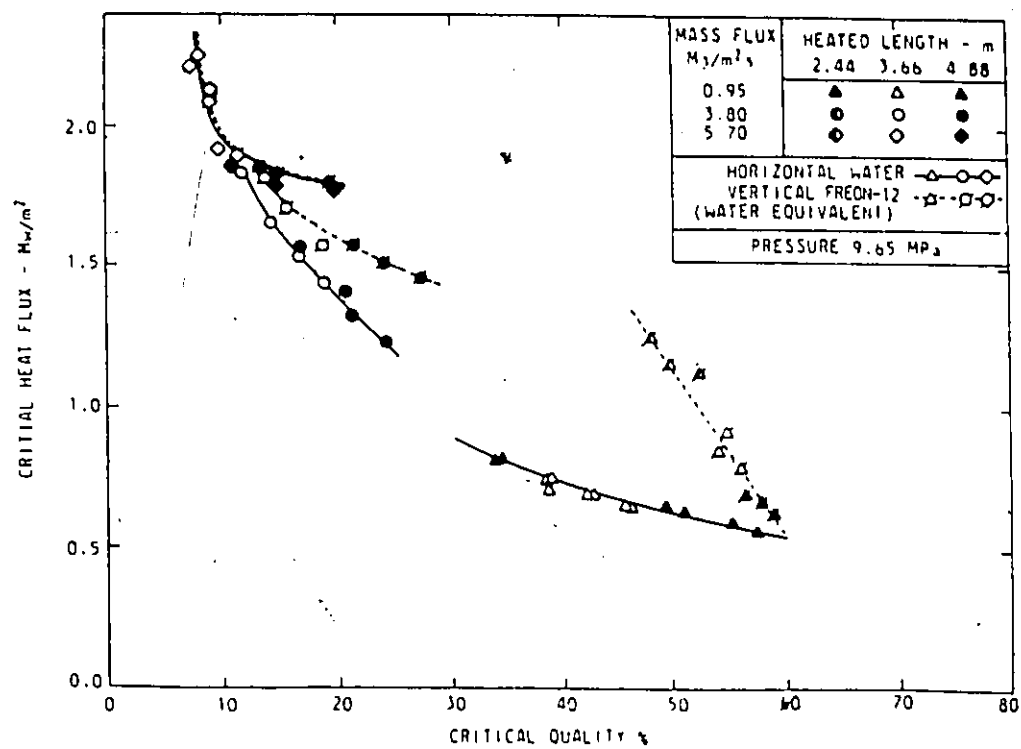


Figure 11. Comparison of Vertical and Horizontal CHF with Water as Coolant at a Pressure of 9.65 MPa (Merilo, 1977).

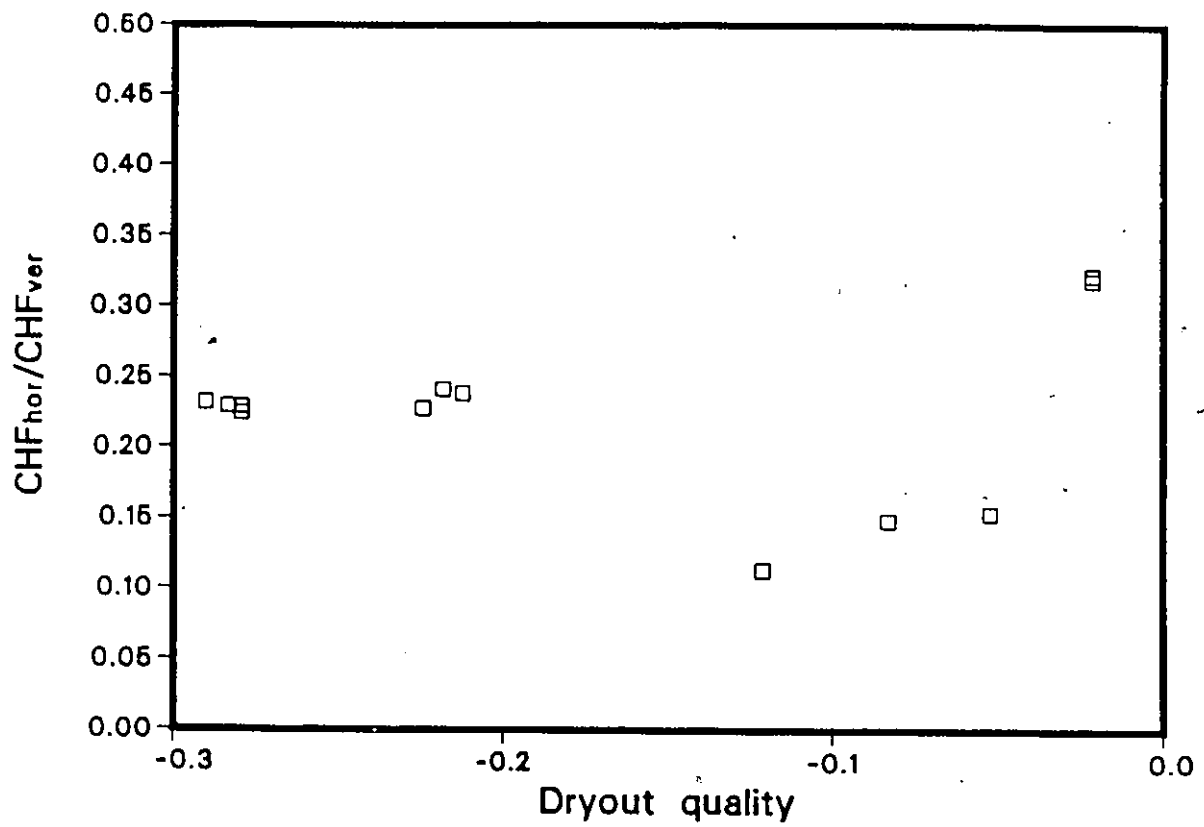


Figure 12. Critical Heat Flux at Subcooled Condition (Becker, 1971).

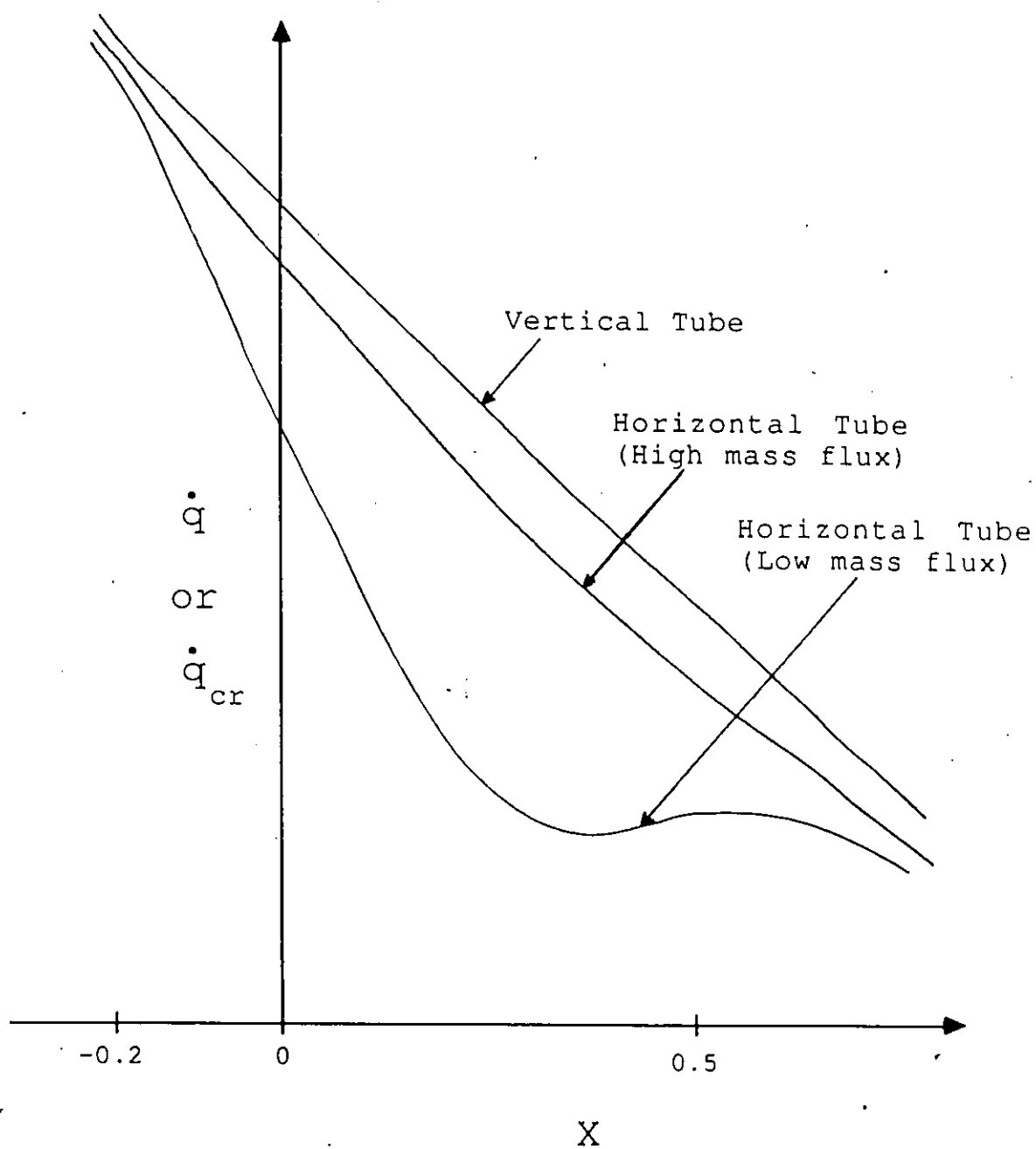


Figure 13. Critical Heat Flux as a Function of Quality for Both Vertical and Horizontal Flow.

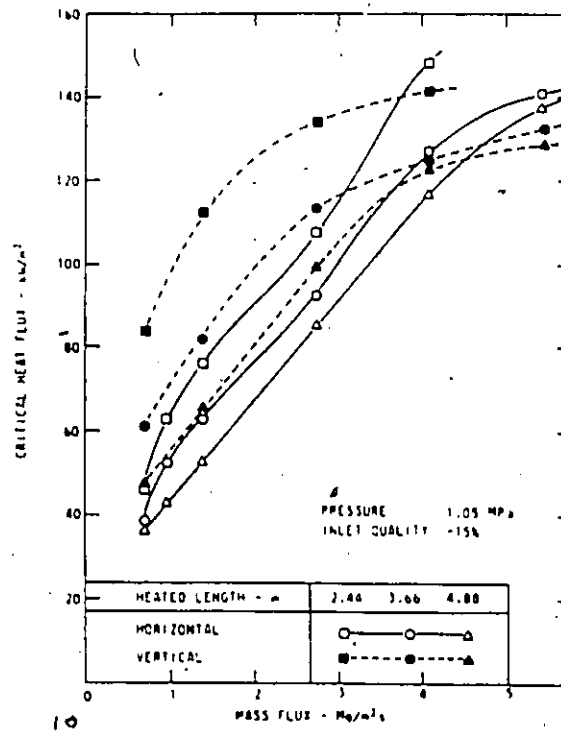


Figure 14. The Effect of Mass Flux on Vertical and Horizontal CHF with Freon-12 at a Pressure of 1.05 MPa (Merilo, 1977).

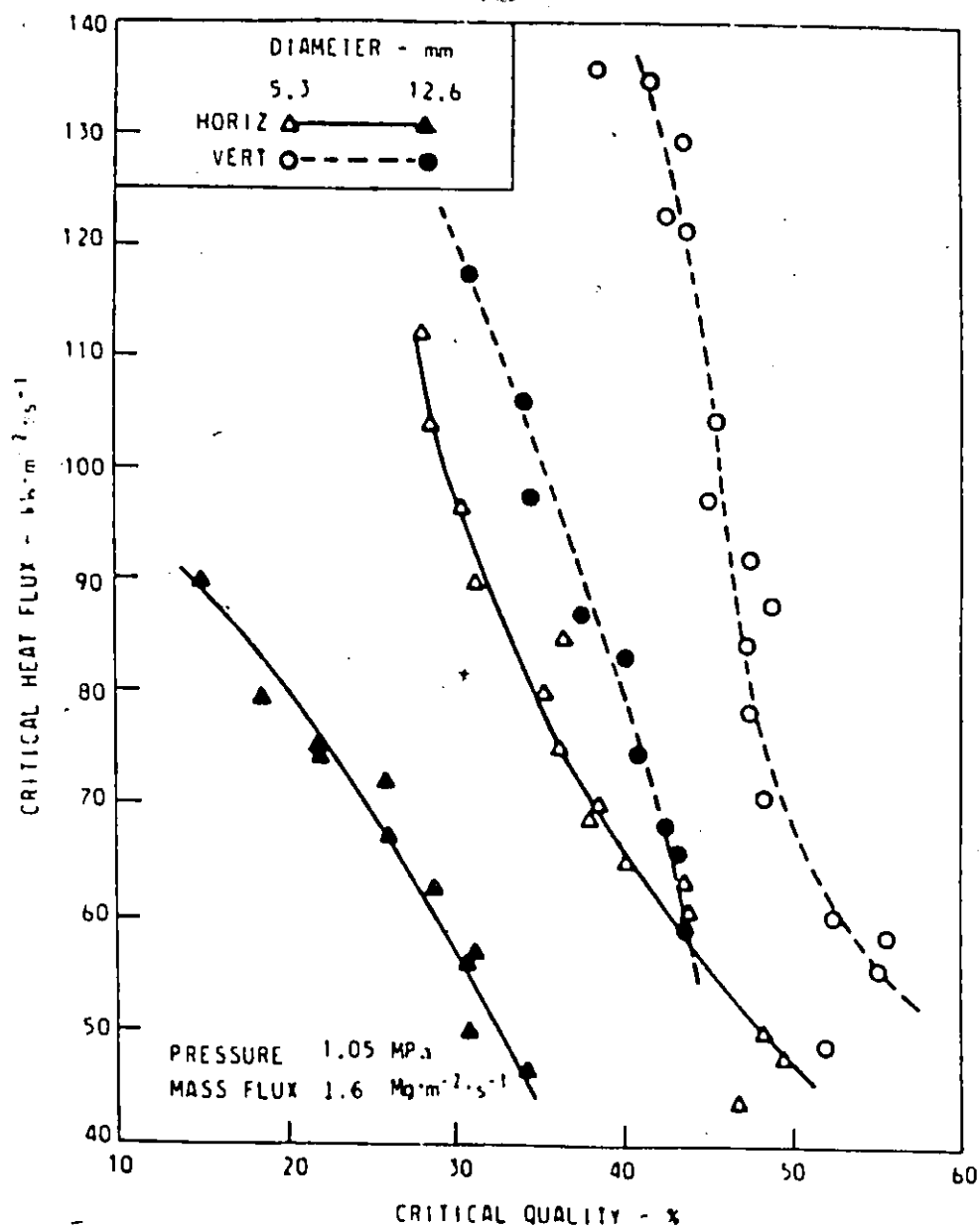


Figure 15. The Effect of Diameter on CHF (in Vertical and Horizontal Flow on a Local Conditions Basis (Merilo and Ahmad, 1979).

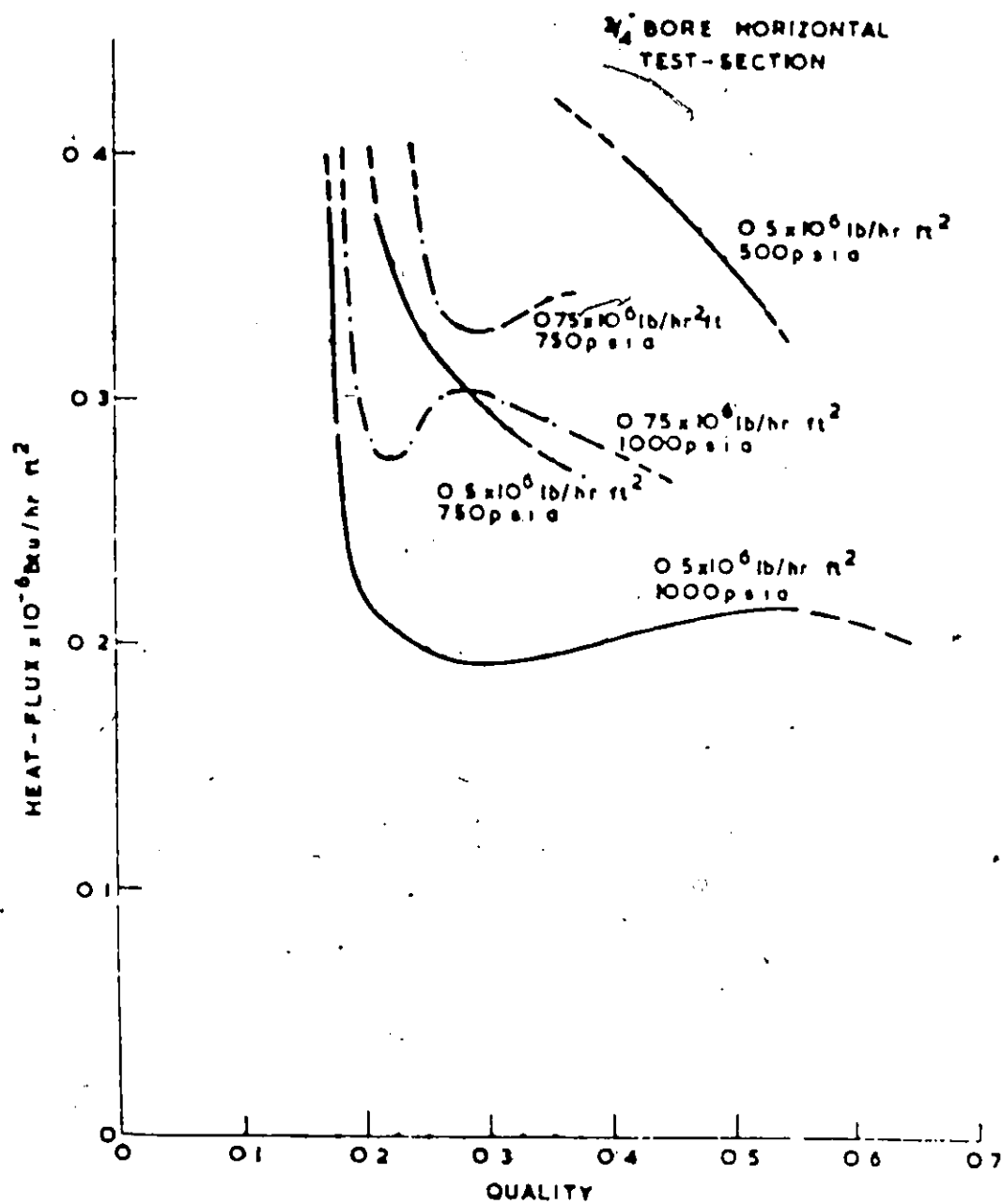


Figure 16. Effect of Pressure on Horizontal CHF (Robertson, 1973).

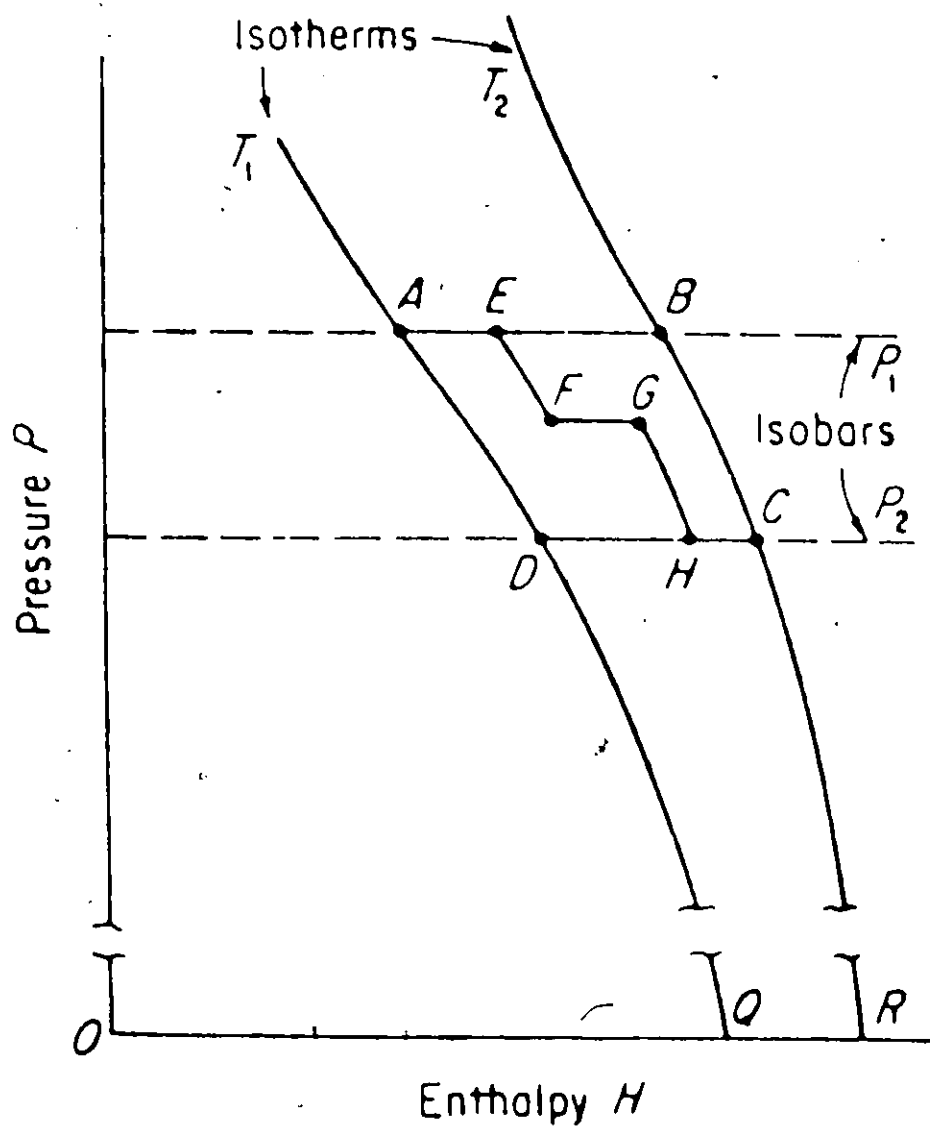


Figure 17. Schematic Diagram Showing Possible Enthalpy Changes between Any Two States (Reid et al., 1977).

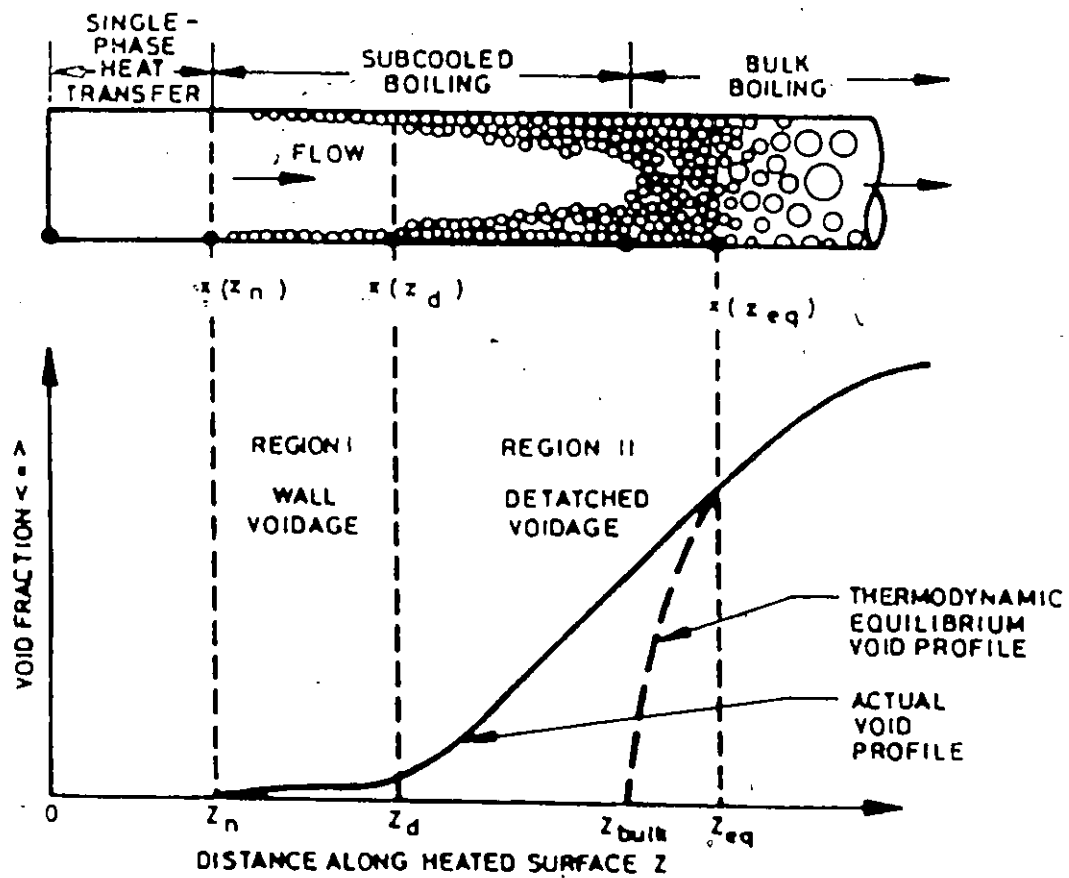


Figure 18. Onset of Bubble Detachment in Flow Boiling.

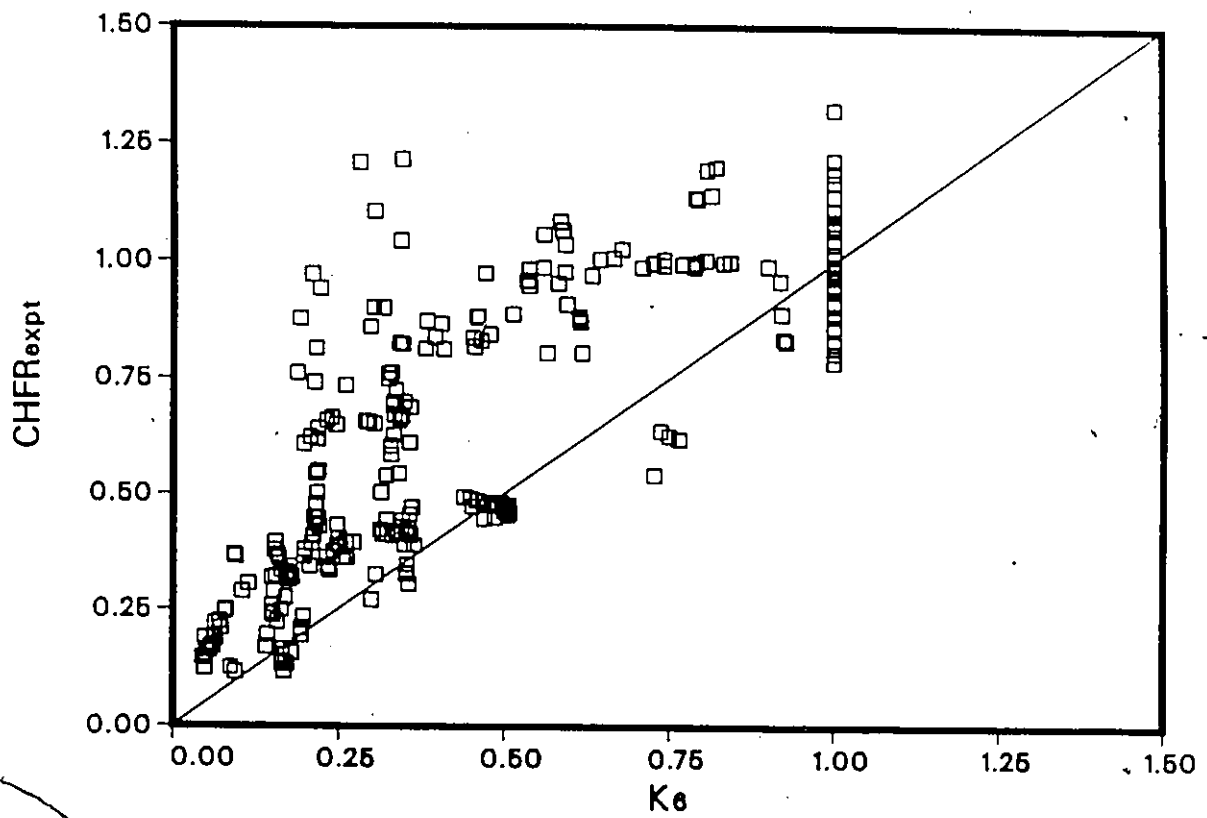


Figure 19. Comparison of K_0 Prediction against Experimental CHF Ratio (Eq.2.21).

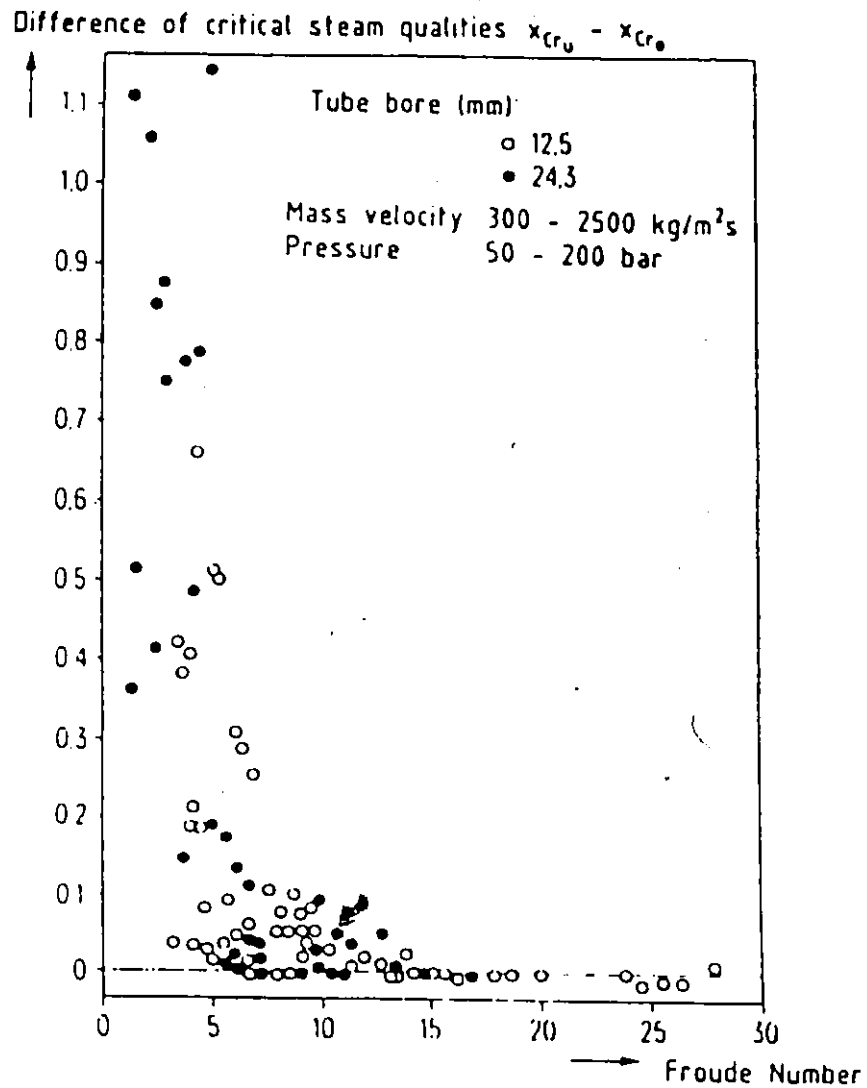


Figure 20. Difference of the Critical Steam Quality as a Function of the Froude Number Defined in Eq. (5.5) (Kholer and Hein, 1986).

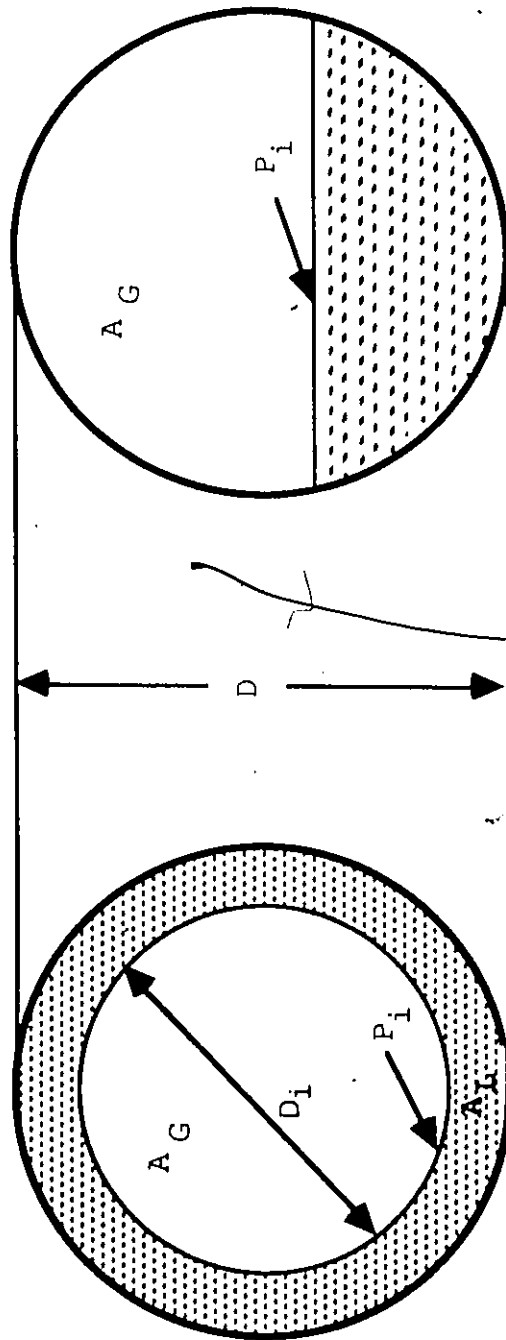


Figure 21. Interface Perimeters for Annular Flow and Equilibrium Stratified Flow.

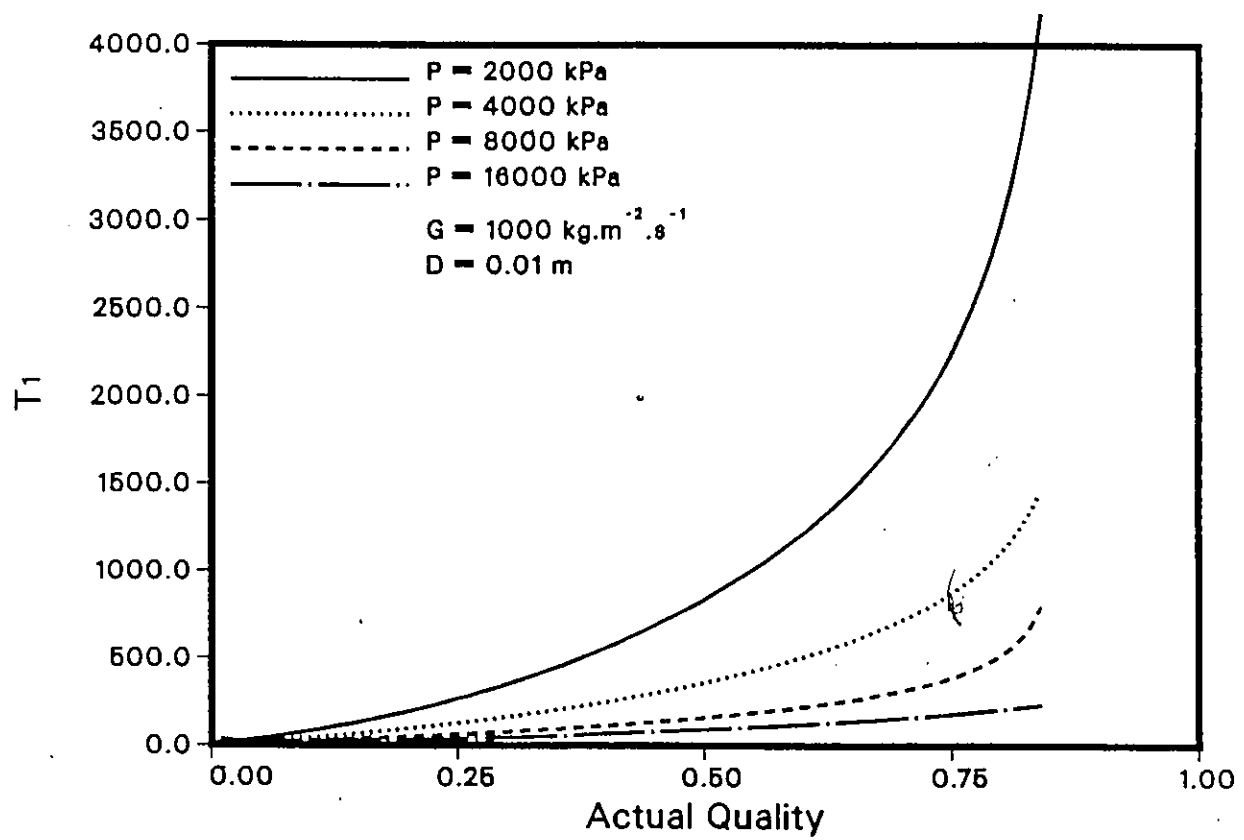


Figure 22a. Parametric Trend of T_1 with Quality.

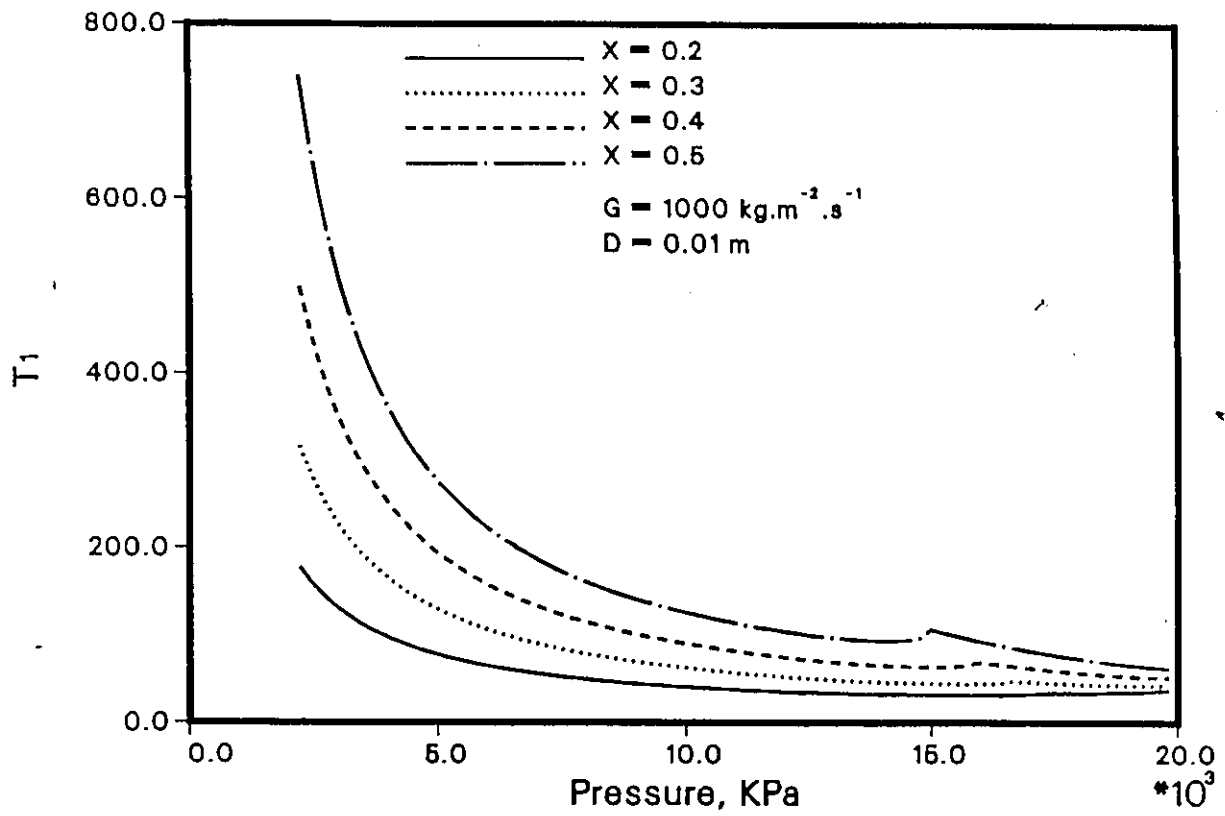


Figure 22b: Parametric Trend of T_1 with Pressure.

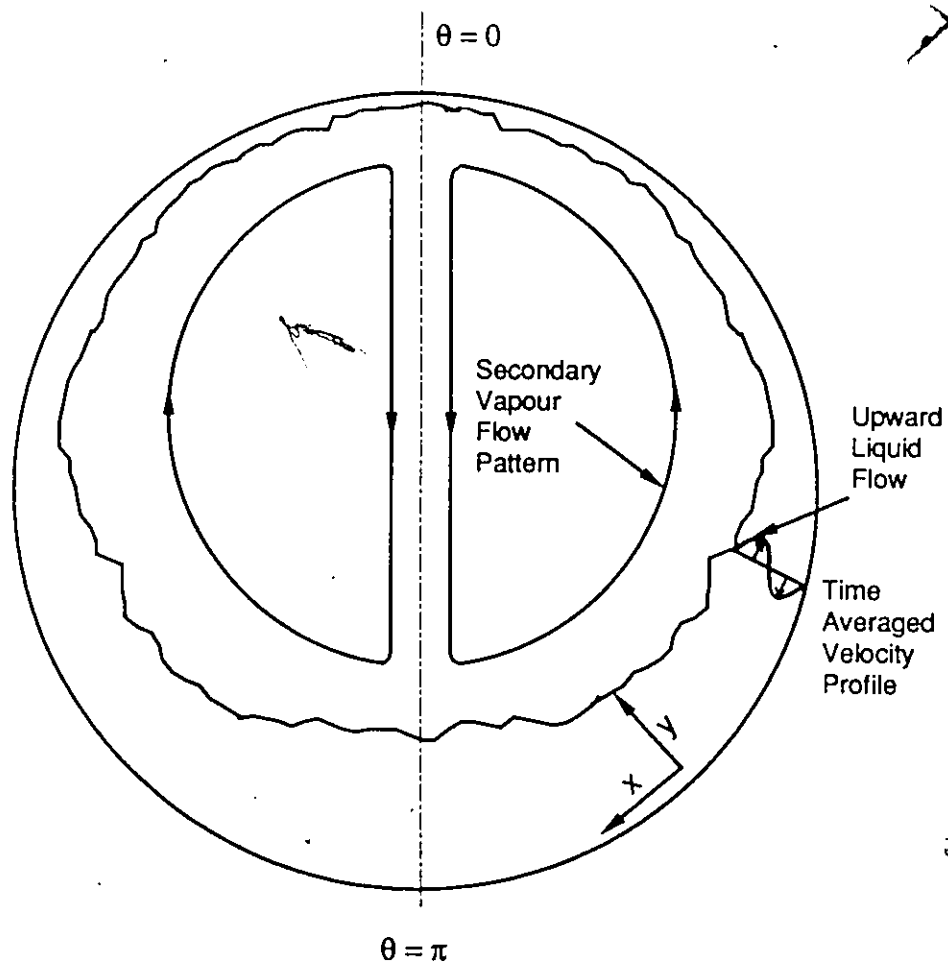


Figure 23. Secondary Vapor Flow and Upward Liquid Flow in a Cross-sectional View of a Horizontal Annular Flow.

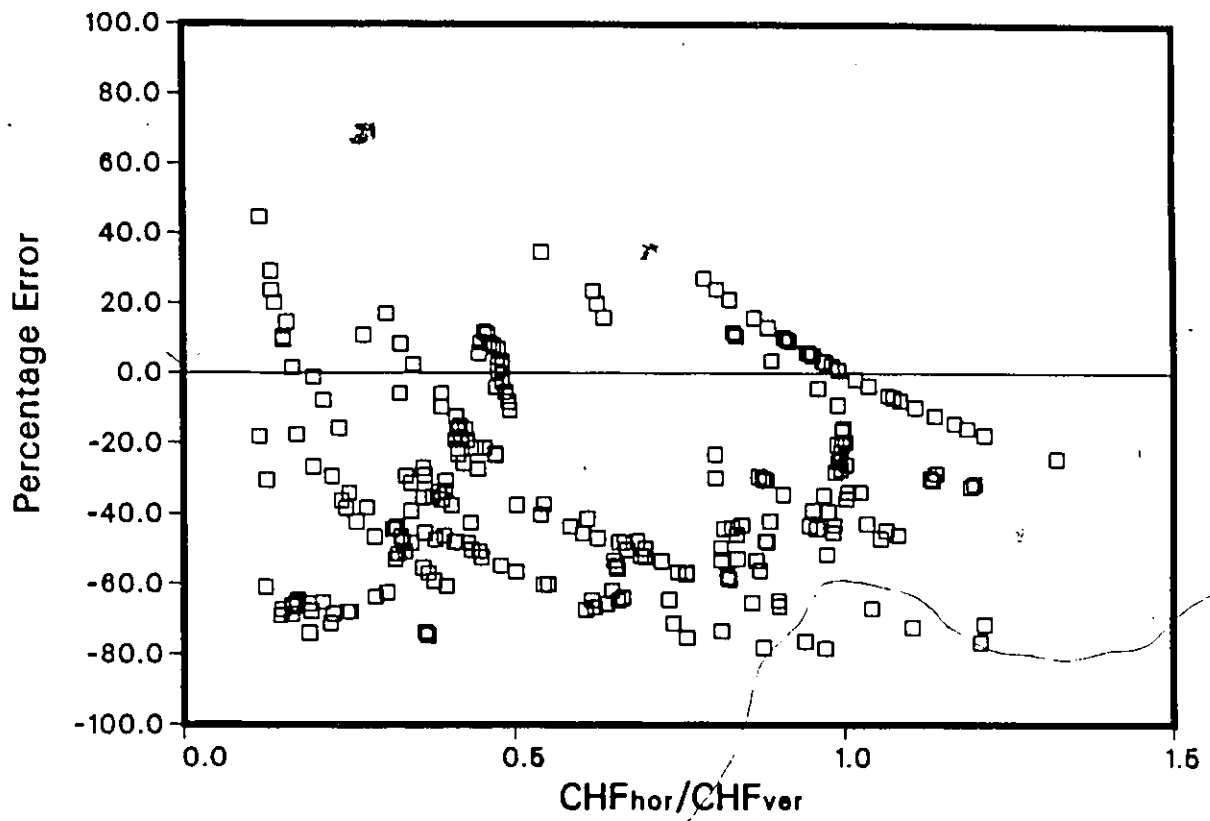


Figure 24. Prediction Error vs. Experimental CHF Ratio (Eq. 2.25).

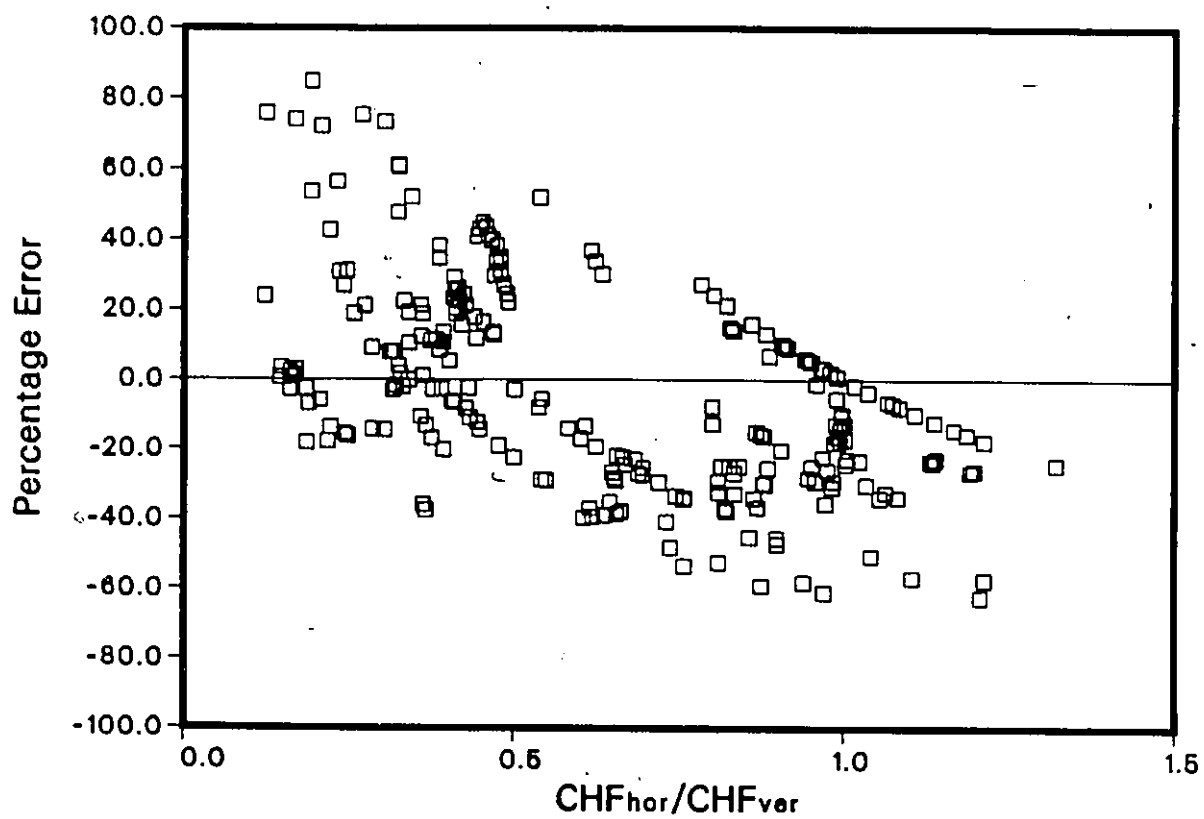


Figure 25. Prediction Error vs. Experimental CHF Ratio (Eq. 6.3).

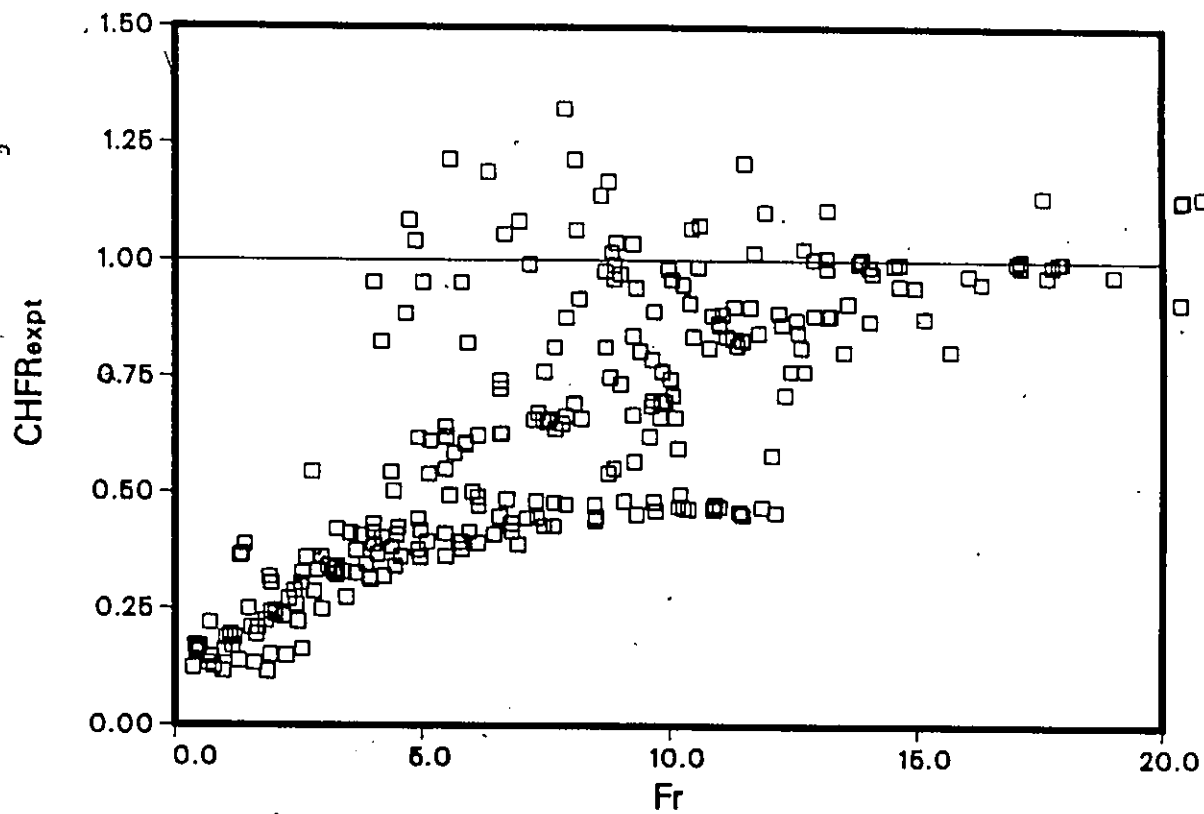


Figure 26a. Experimental CHF Ratio vs. Fr .

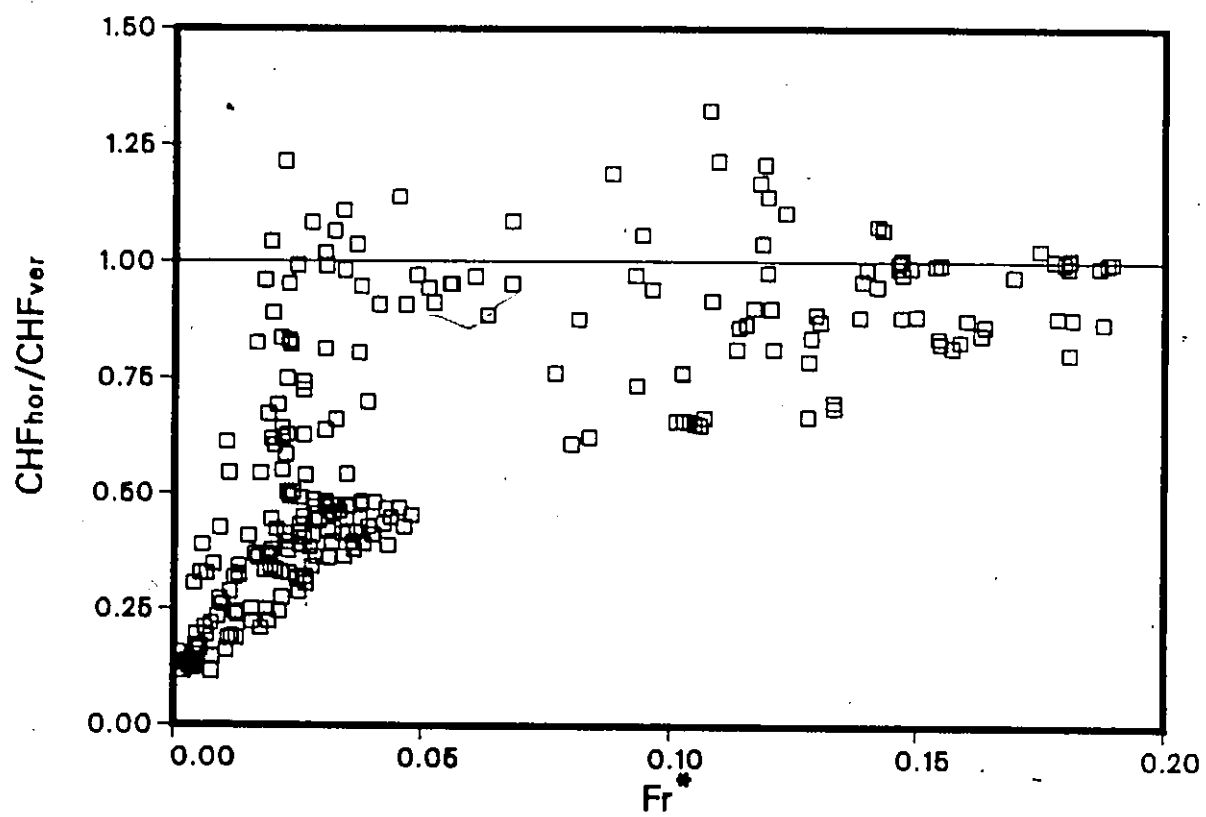


Figure 26b. Experimental CHF ratio vs. Fr^* .

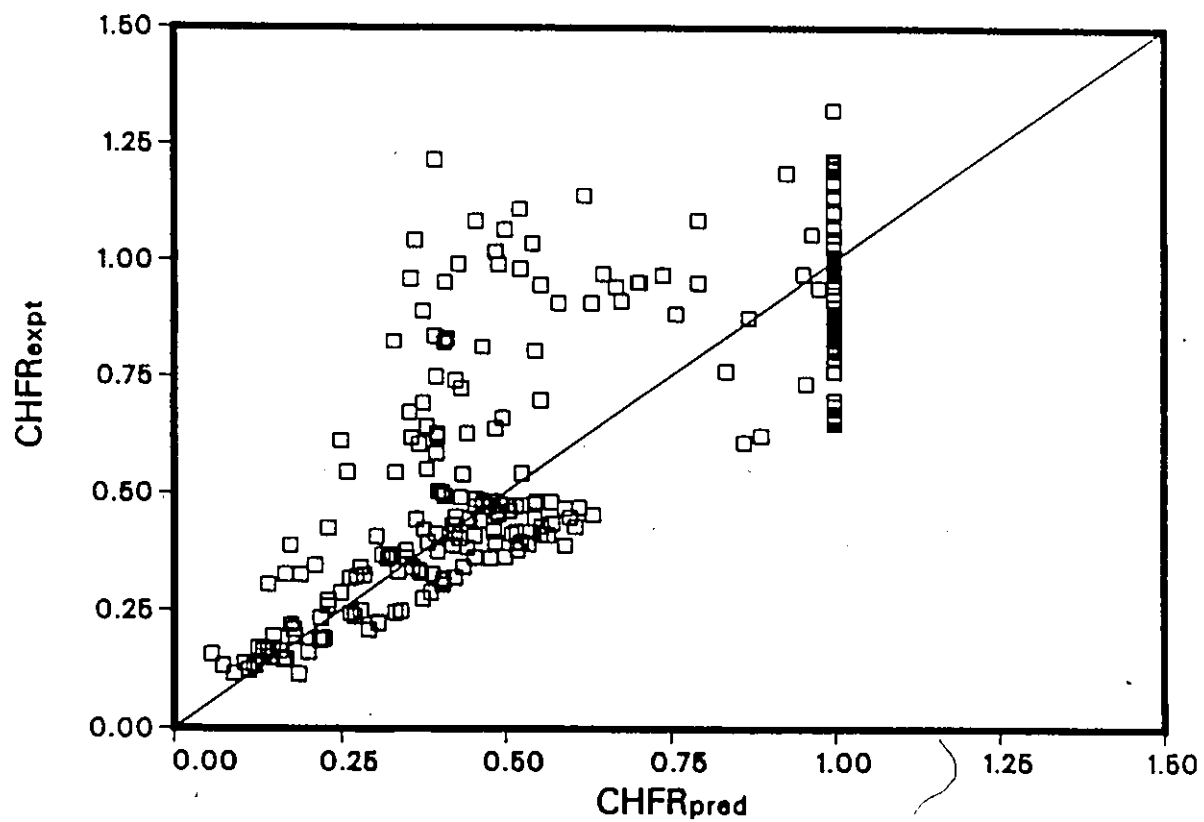


Figure 27. Comparison of Experimental and Predicted CHF Ratio (Eq. 6.6).

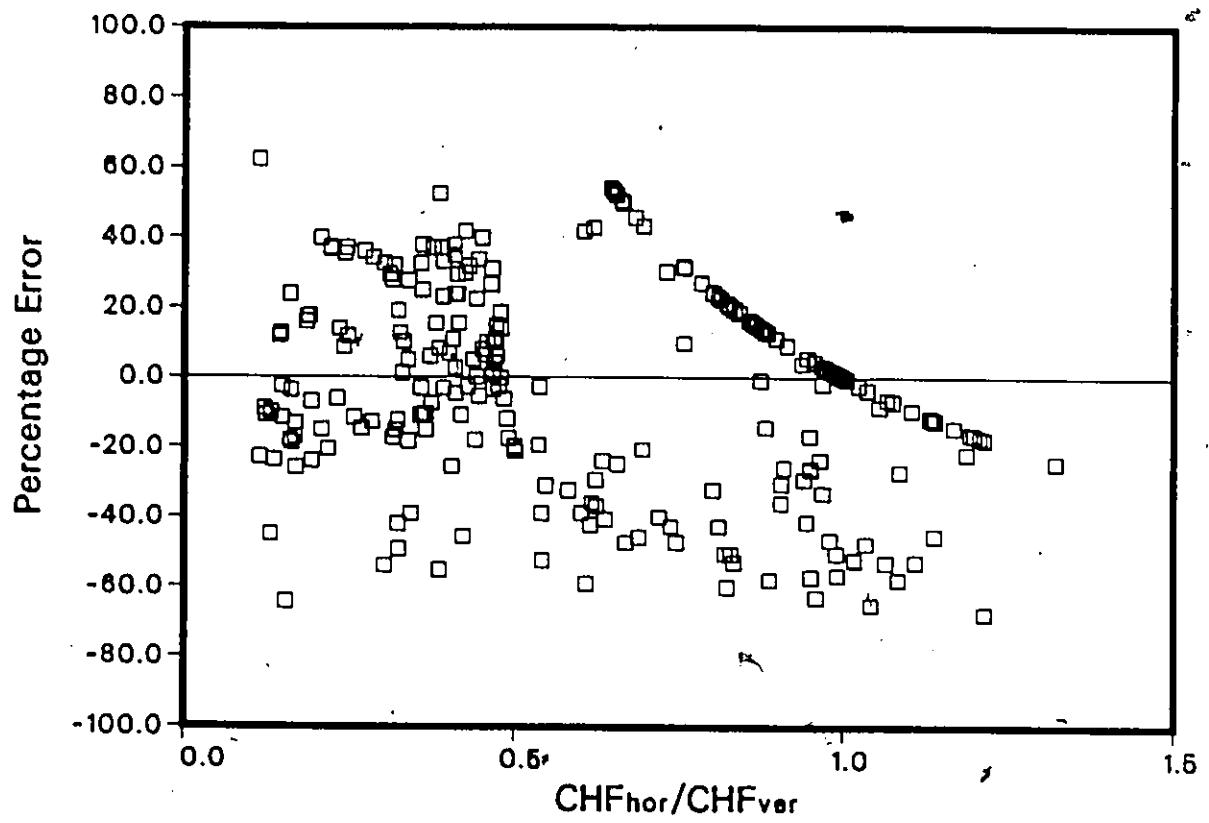


Figure 28. Prediction Error vs. CHF Ratio (Eq. 6.6).

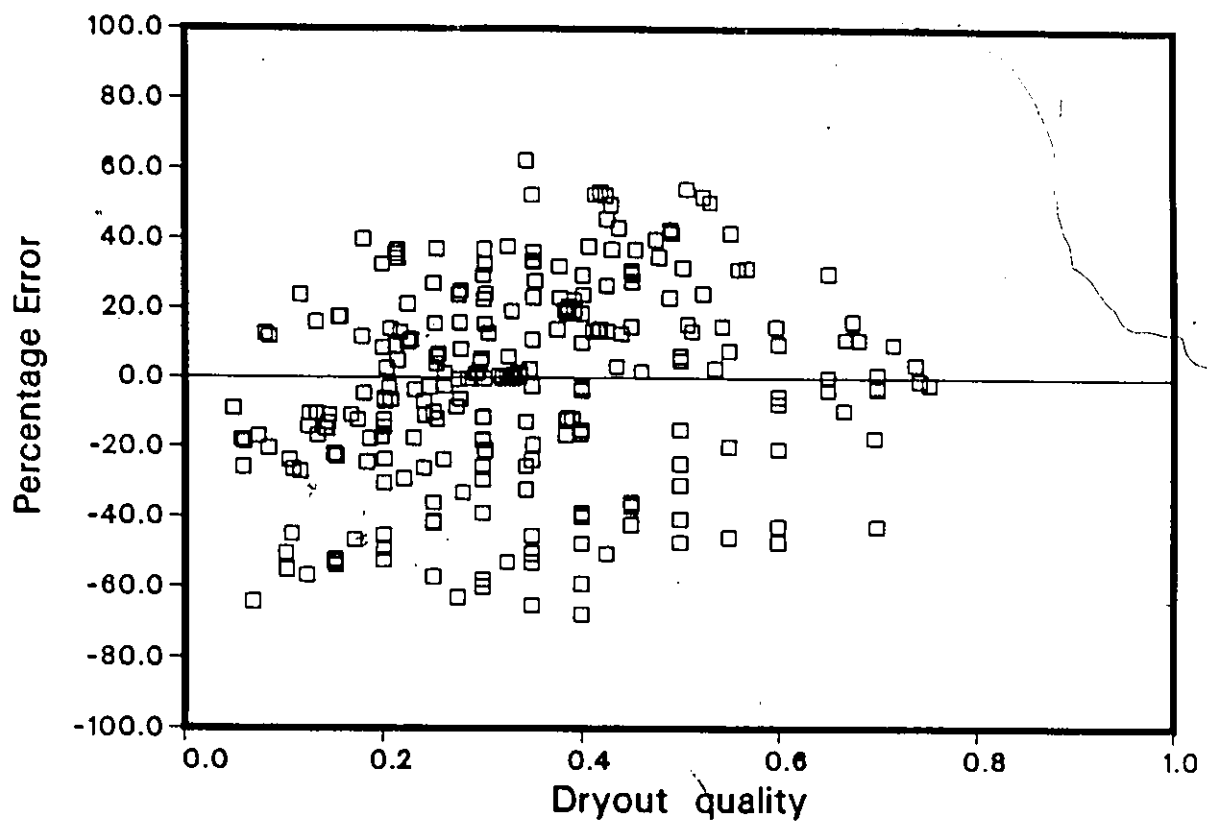


Figure 29. Prediction Error vs. Quality (Eq. 6.6).

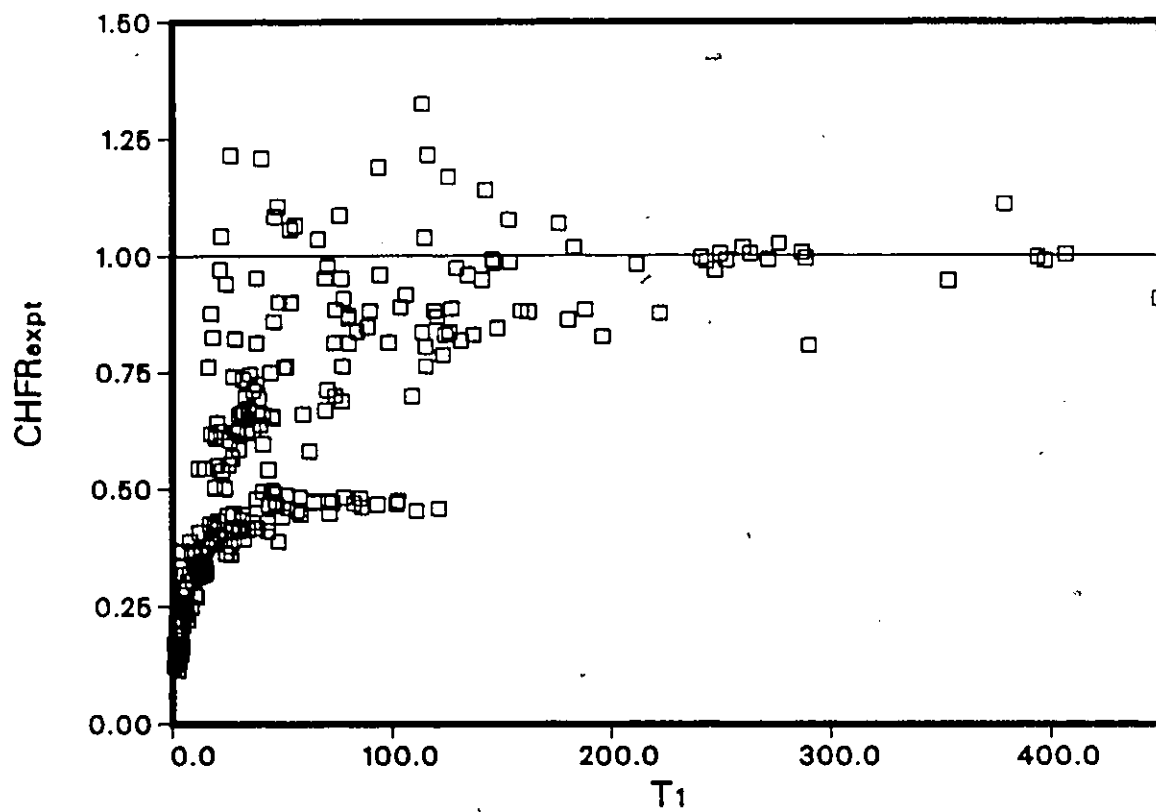


Figure 30. CHF Ratio as a Function of T_1 .

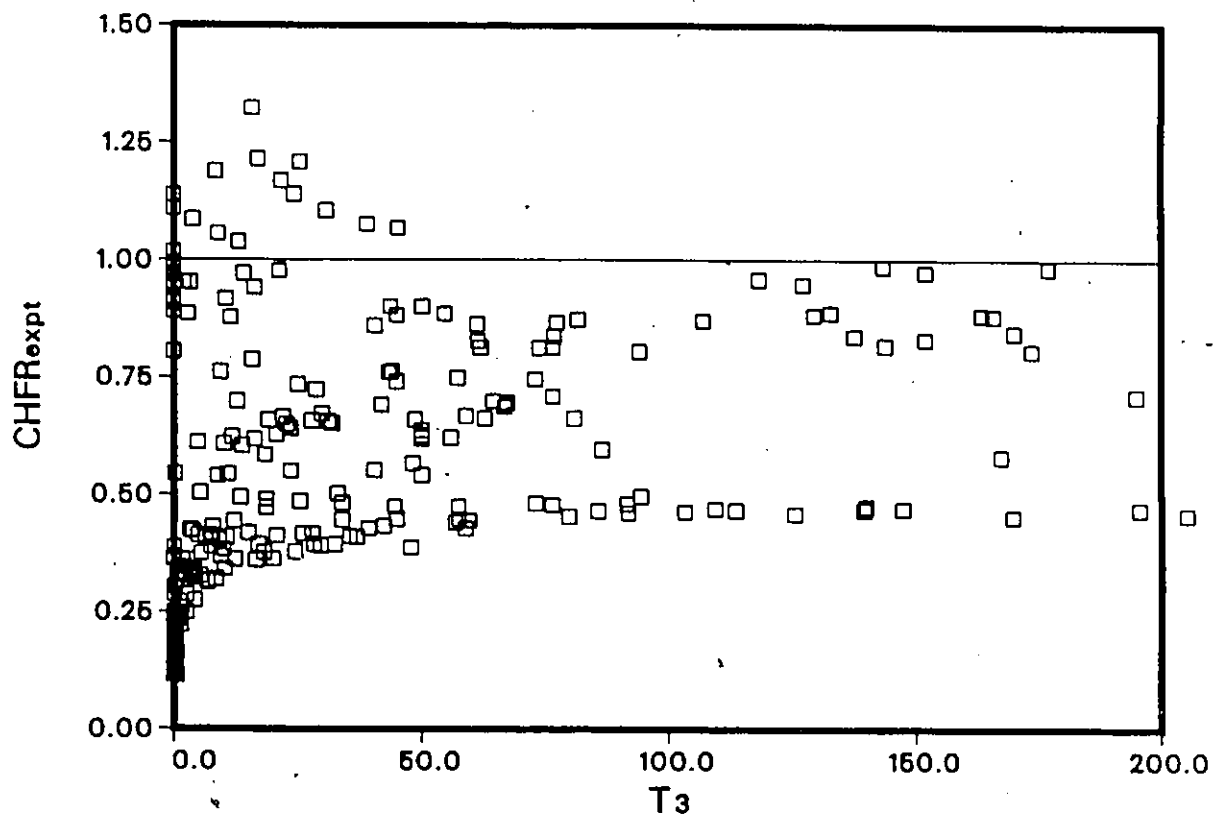


Figure 31. CHF ratio as a Function of T_3 .

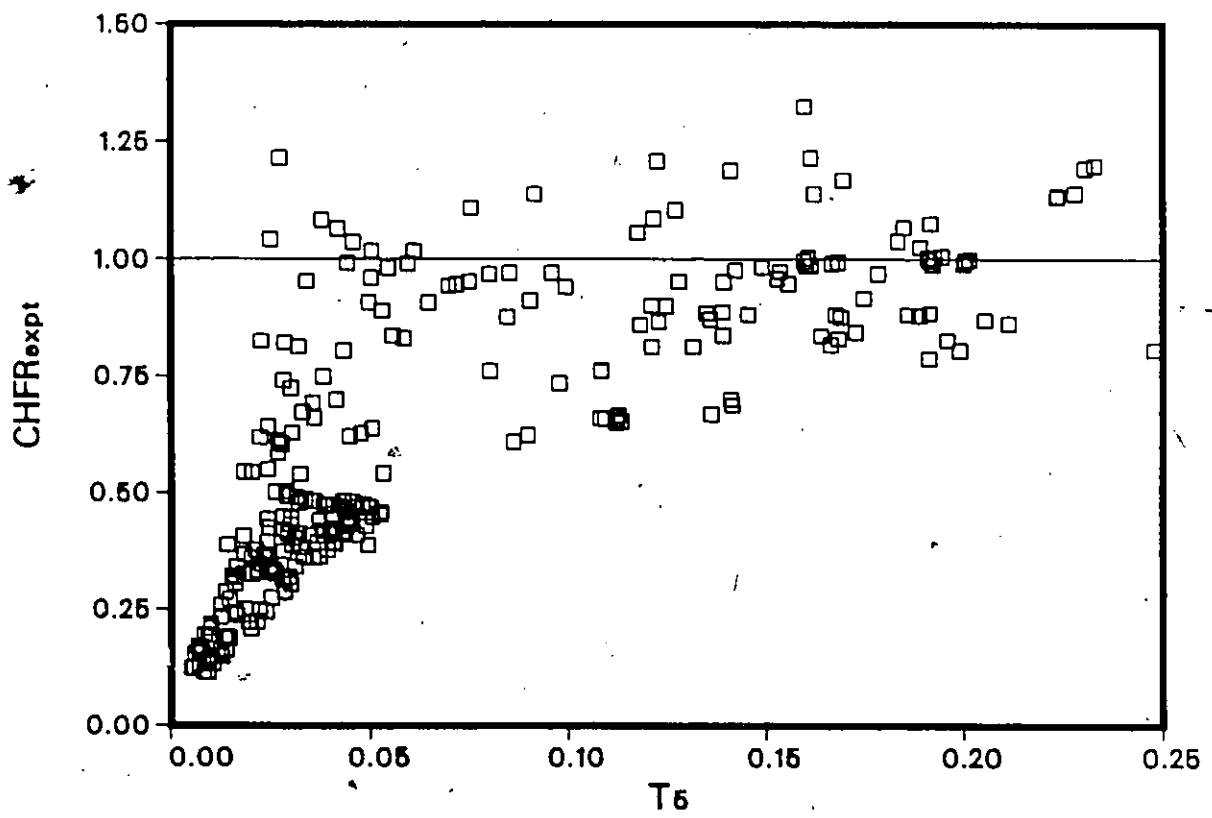


Figure 32. CHF Ratio as a Function of T_5 .

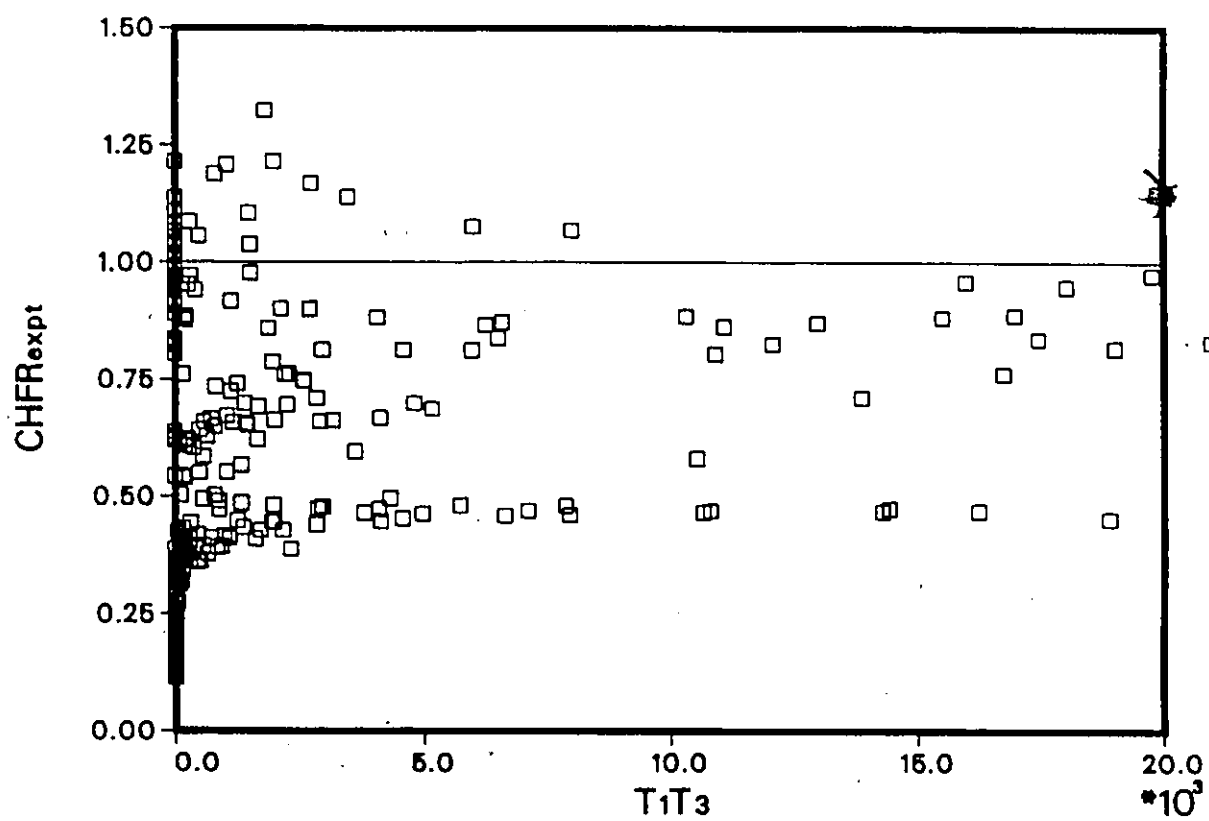


Figure 33. CHF Ratio as a Function of $(T_1 \times T_3)$.

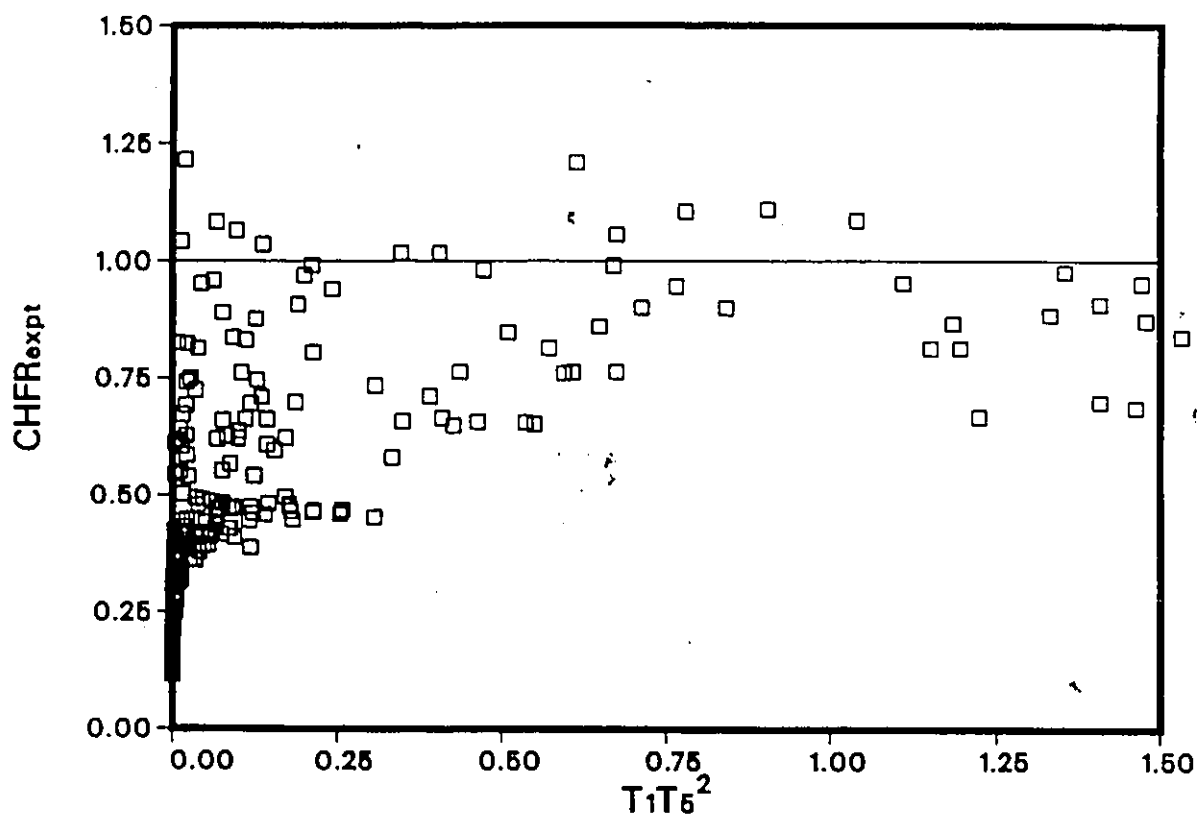


Figure 34. CHF Ratio as a Function of $(T_1 \times T_5^2)$.

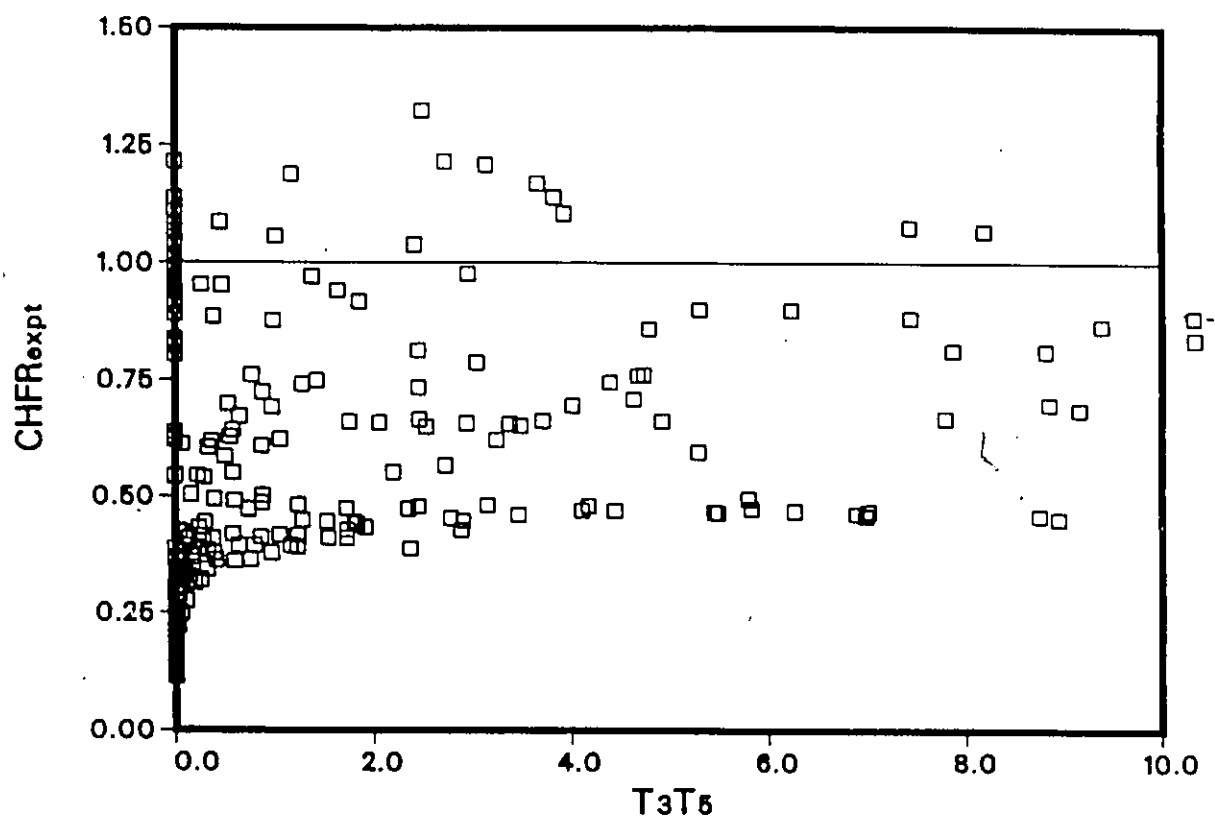


Figure 35. CHF Ratio as a Function of $(T_3 \times T_5)$.

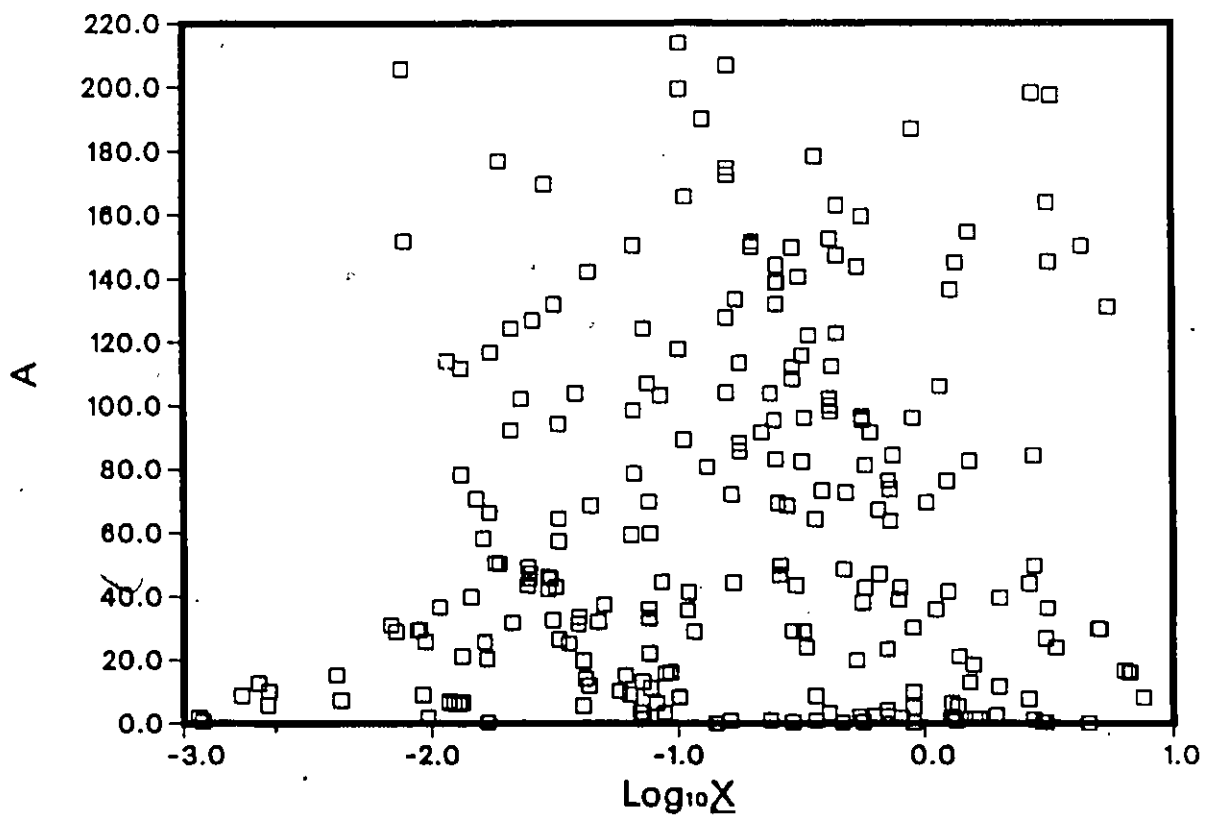


Figure 36. Variation of A with Martinelli's Parameter.

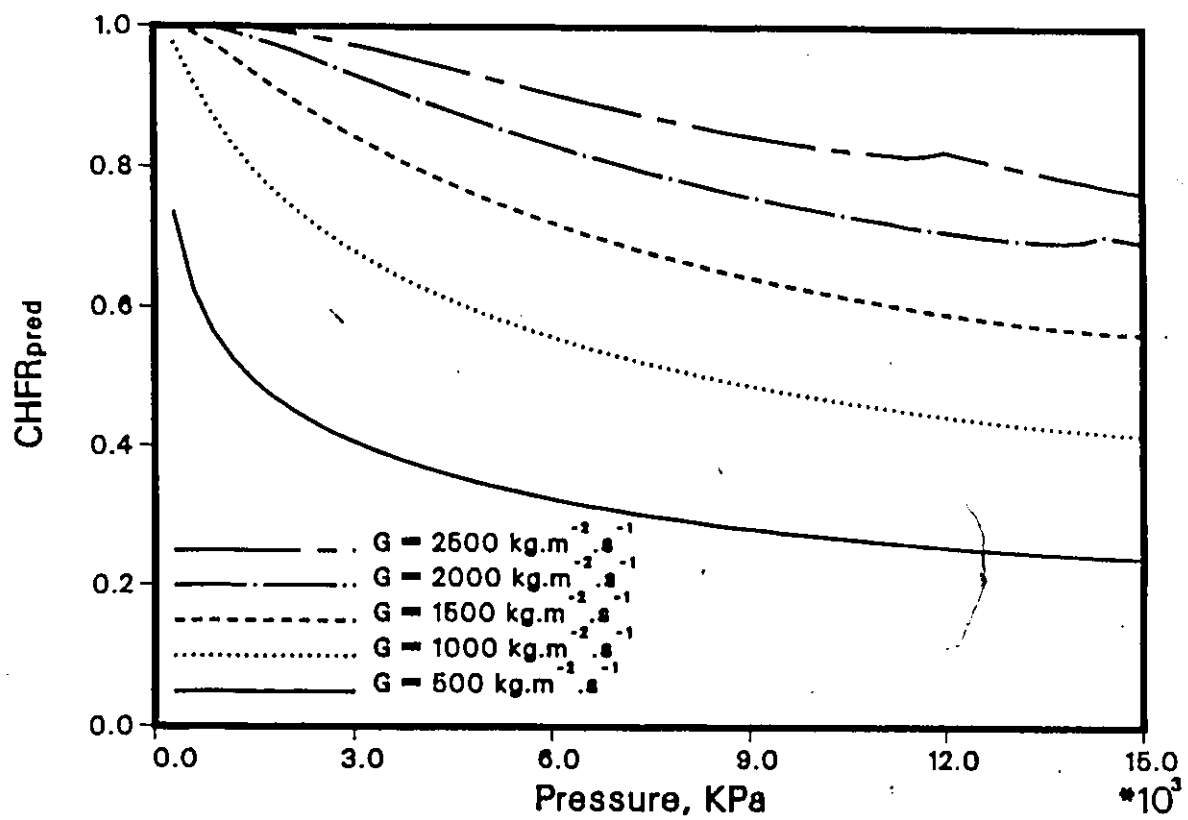


Figure 37a. Predicted CHF Ratio as a Function of Pressure,
 $D = 0.01\text{m}$ and $X_{\text{cr}} = 0.30$.

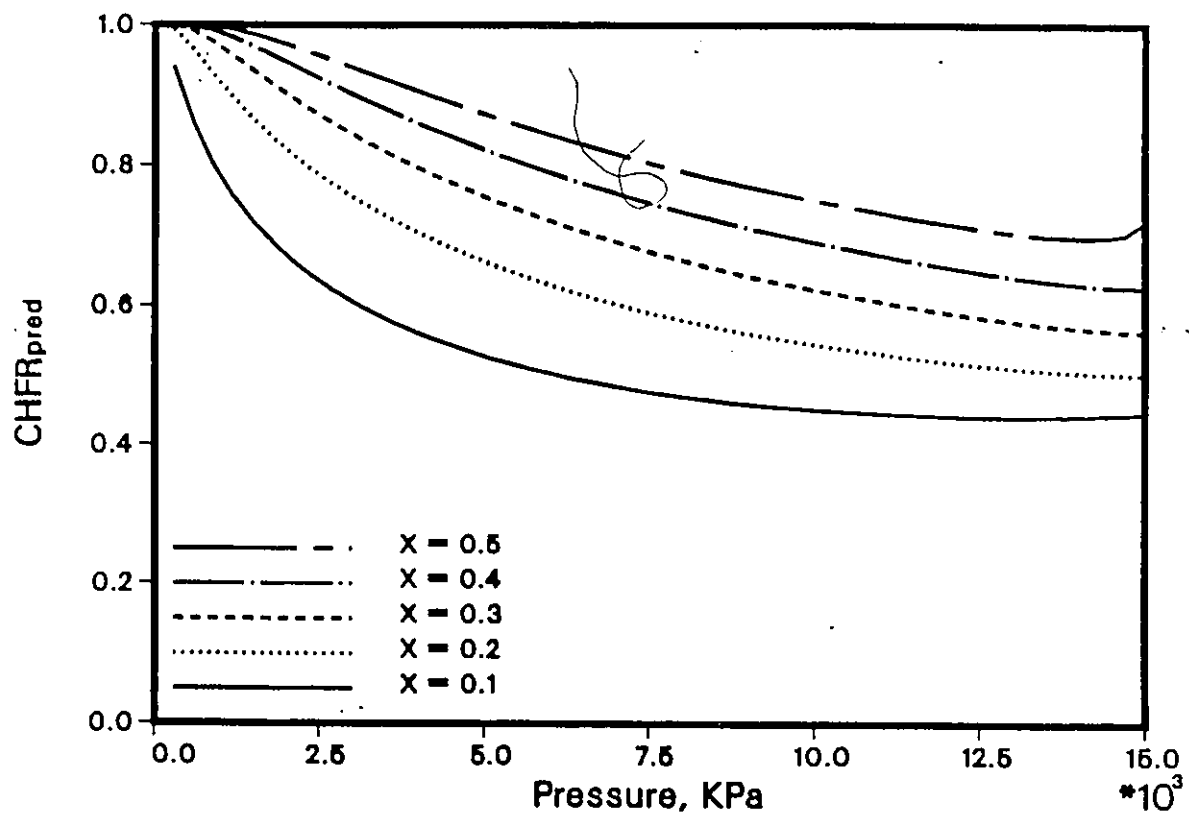


Figure 37b. Predicted CHF Ratio as a Function of Pressure,

$$D = 0.01m \text{ and } G = 1500kg.m^{-2}.s^{-1}.$$

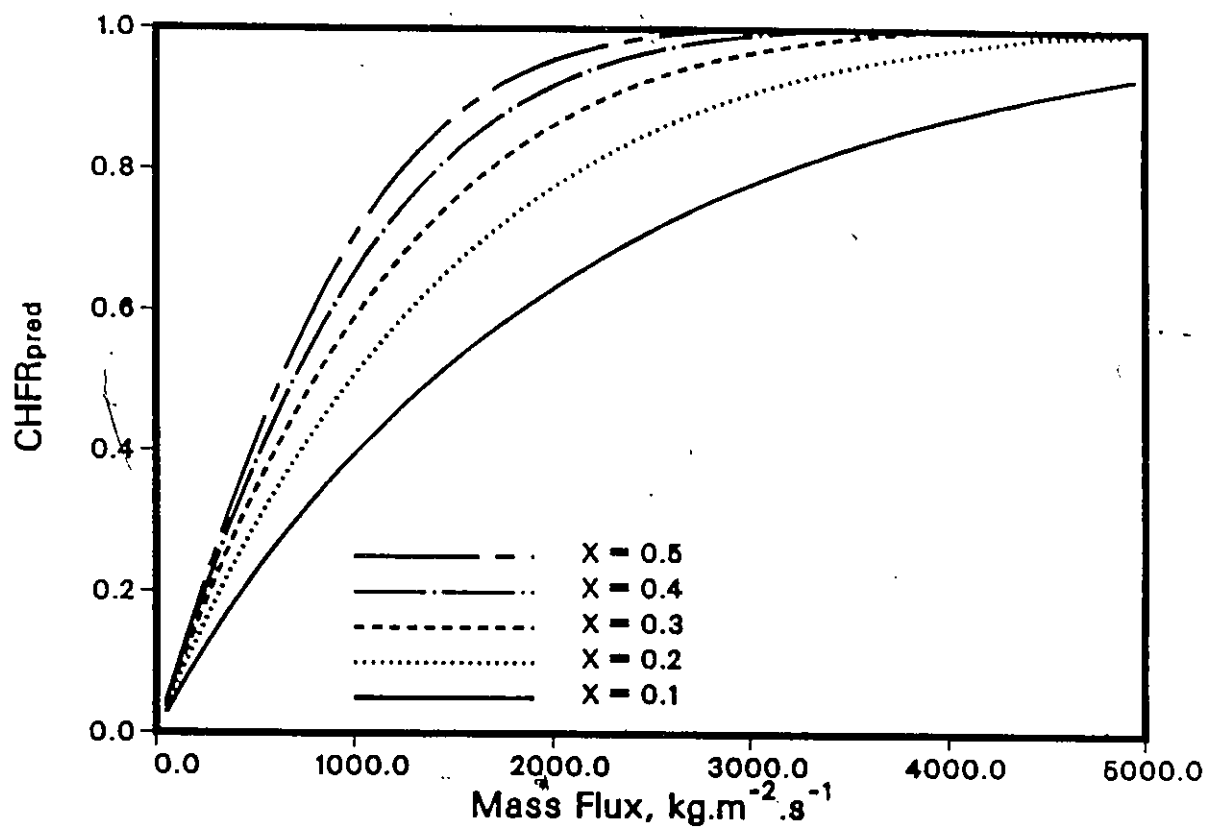


Figure 38a. Predicted CHF Ratio as a Function of Mass Flux,
 $D = 0.01m$ and $P = 5000kPa$.

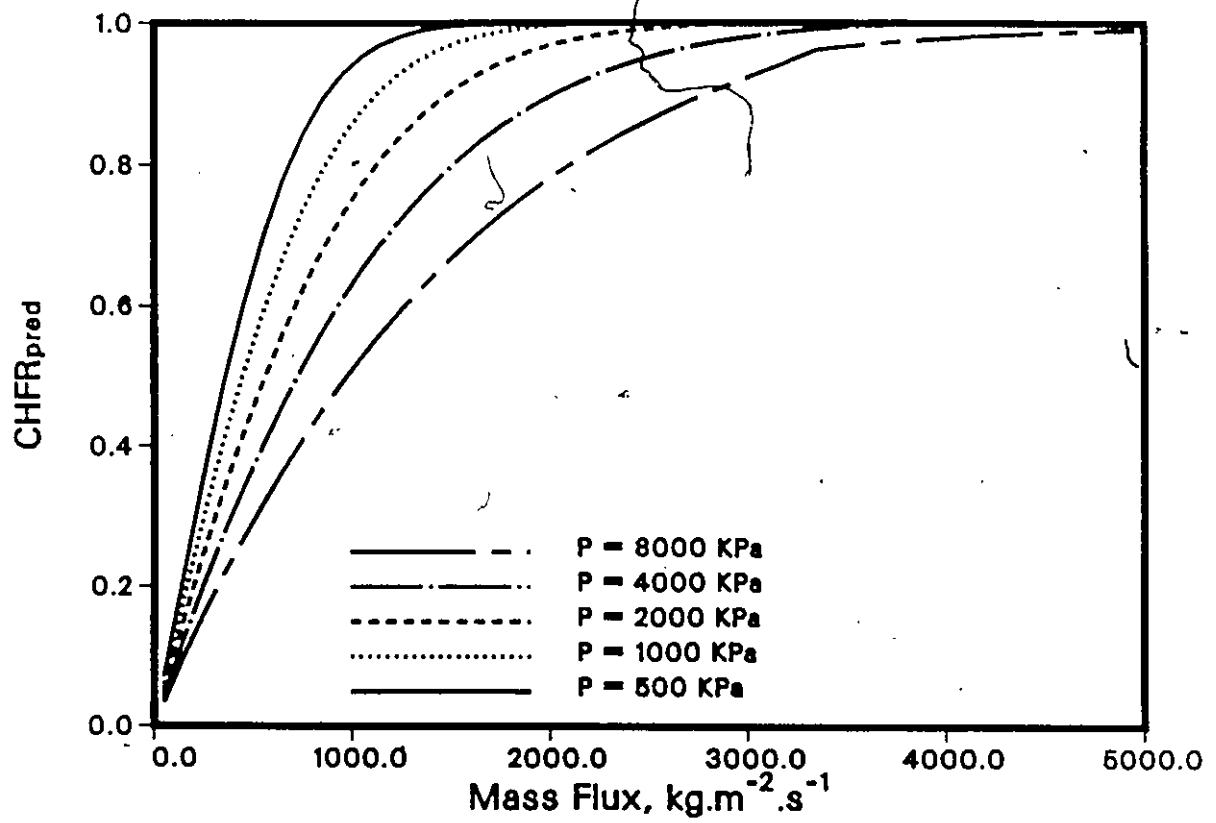


Figure 38b. Predicted CHF Ratio as a Function of Mass Flux, $D = 0.01m$ and $X_{cr} = 0.30$.

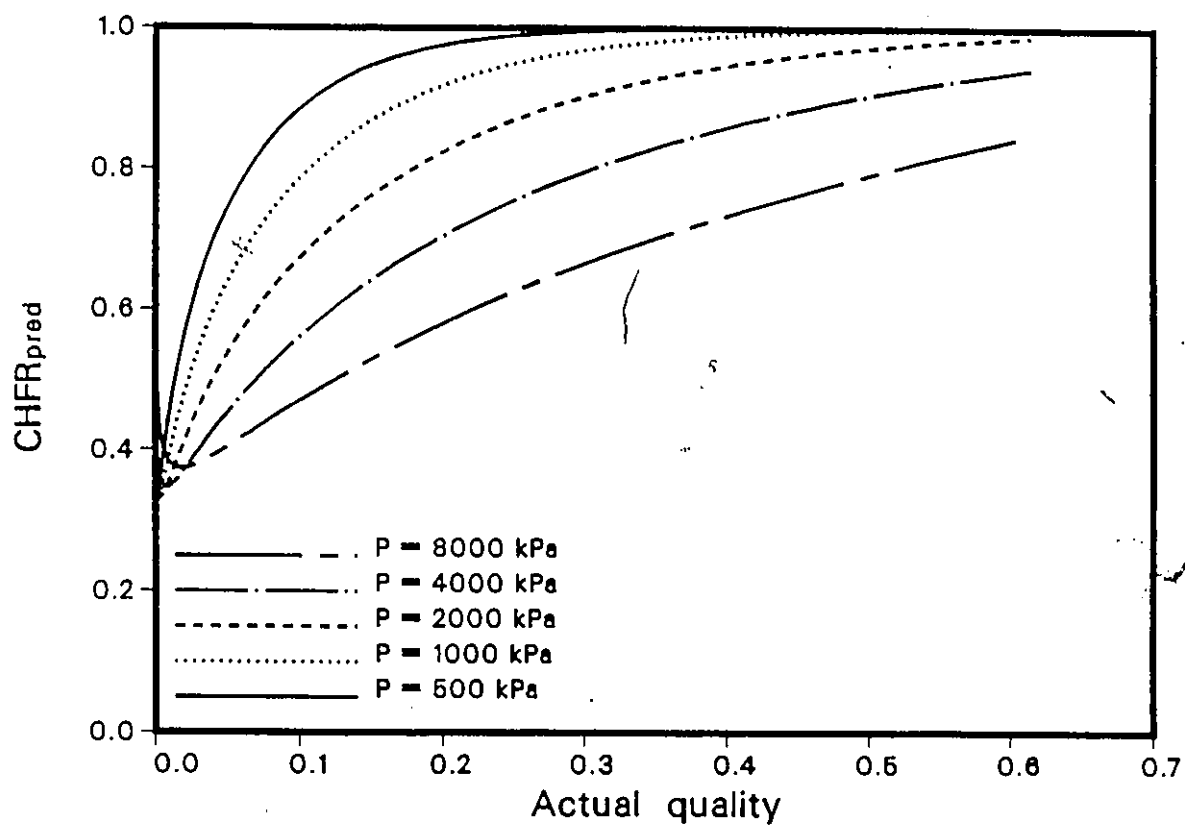


Figure 39a. Predicted CHF Ratio as a Function of Quality,
 $D = 0.01m$ and $G = 1500 kg \cdot m^{-2} \cdot s^{-1}$.

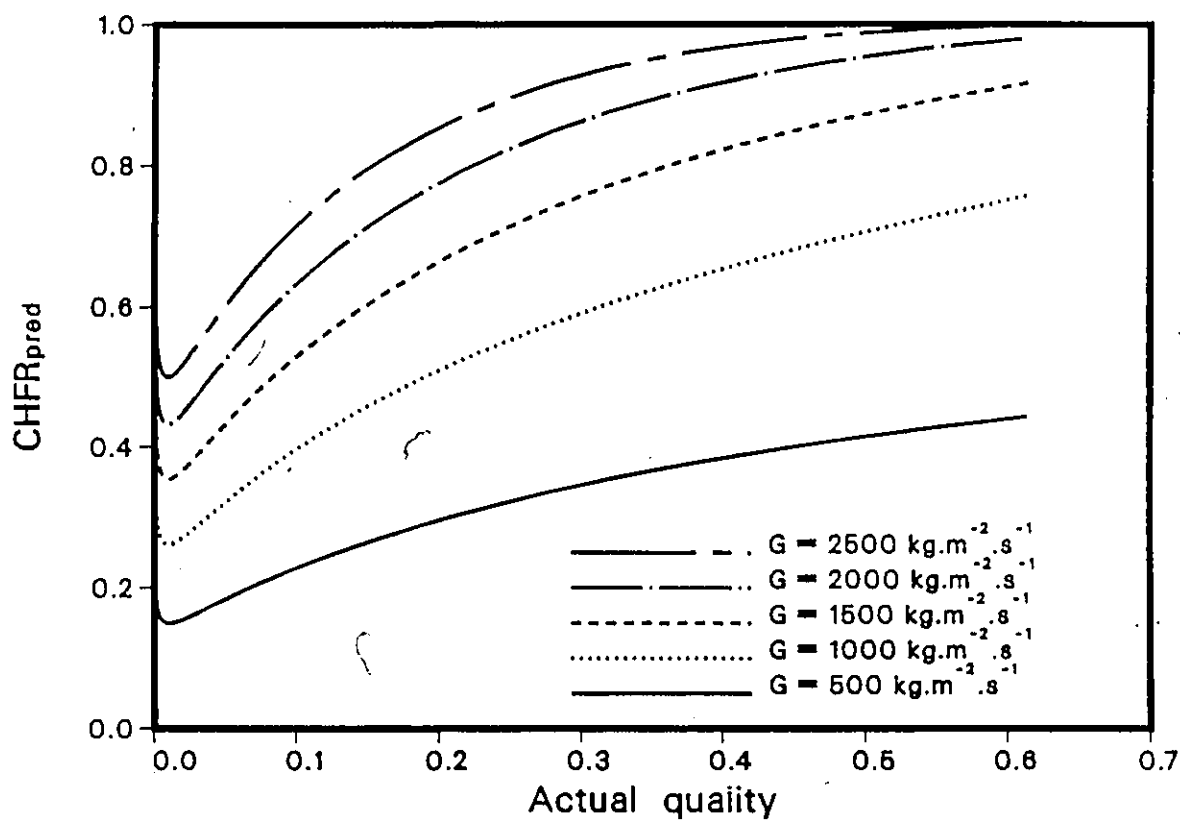


Figure 39b. Predicted CHF Ratio as a Function of Quality,
 $D = 0.01\text{m}$ and $P = 5000\text{kPa}$.

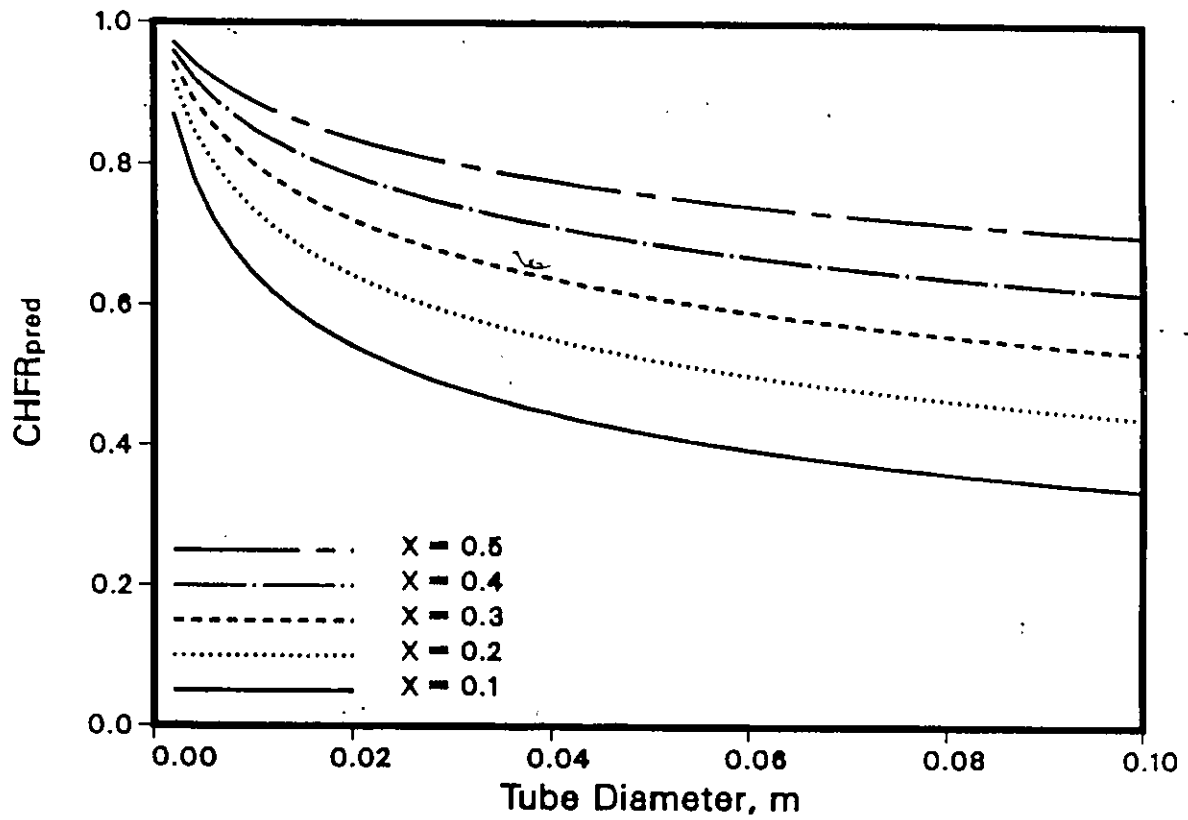
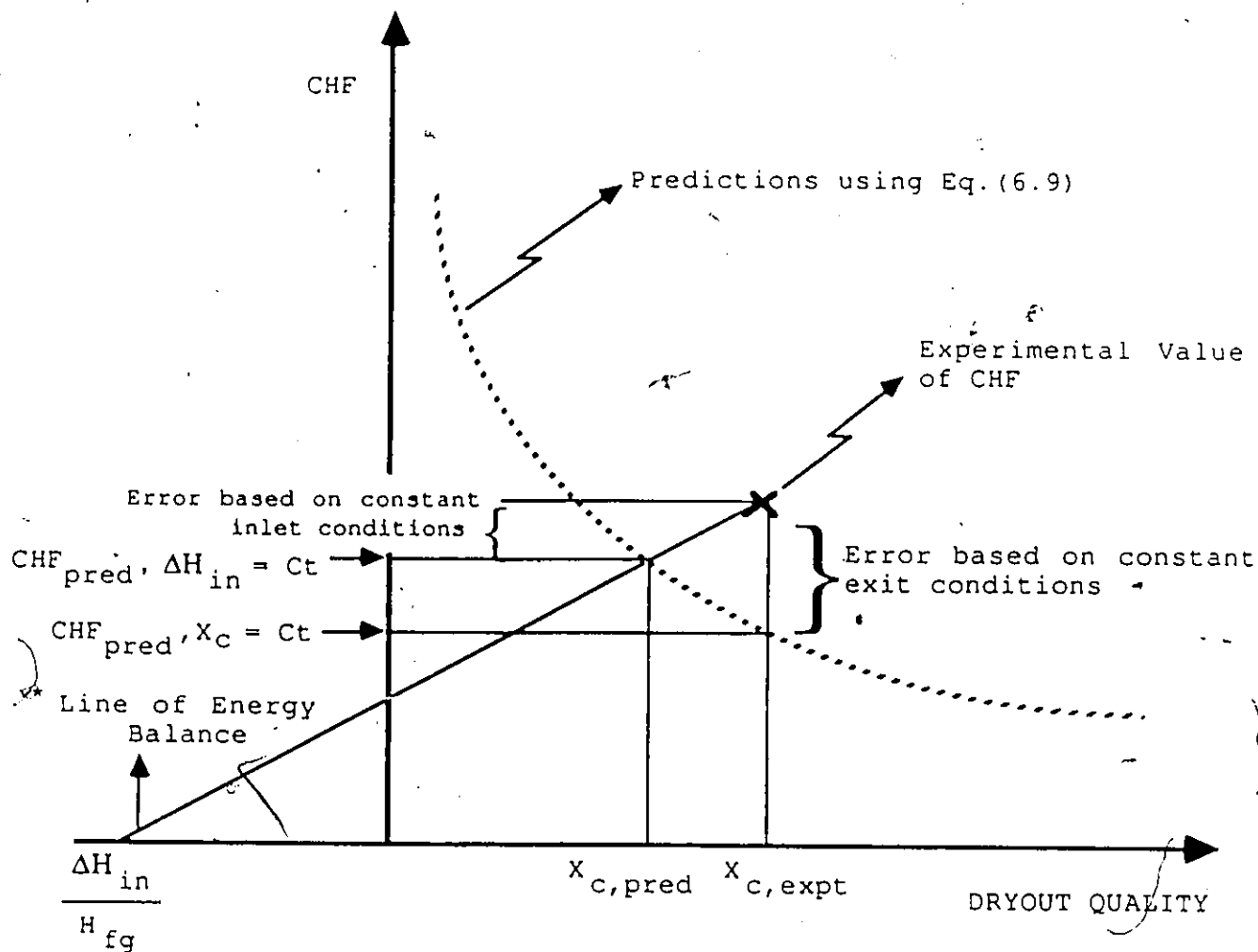


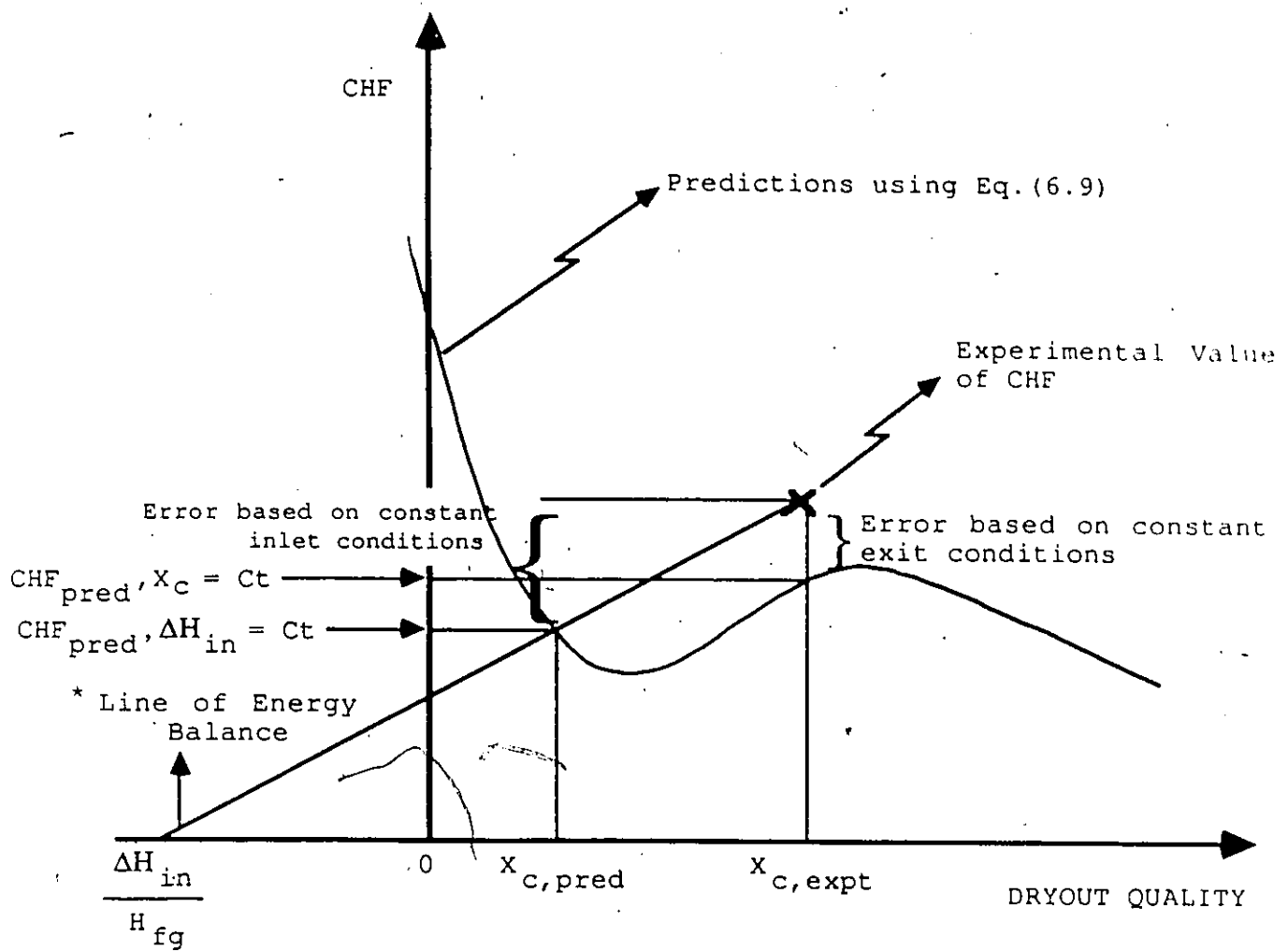
Figure 40. Predicted CHF Ratio as a Function of Diameter,
 $P = 5000 \text{ kPa}$, $G = 1500 \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ and $X_{cr} = 0.30$.



* Energy balance is calculated from the following equation

$$X = \frac{4\dot{q}}{H_{fg} G} \times \frac{L}{D} - \frac{\Delta H_{in}}{H_{fg}}$$

Figure 41a. Error Based on Constant Exit and Inlet Conditions (Horizontal High Flow).



* Energy balance is calculated from the following equation

$$X = \frac{4q}{H_{fg} G} \times \frac{L}{D} - \frac{\Delta H_{in}}{H_{fg}}$$

Figure 41b. Error Based on Constant Exit and Inlet Conditions (Horizontal Low Flow).

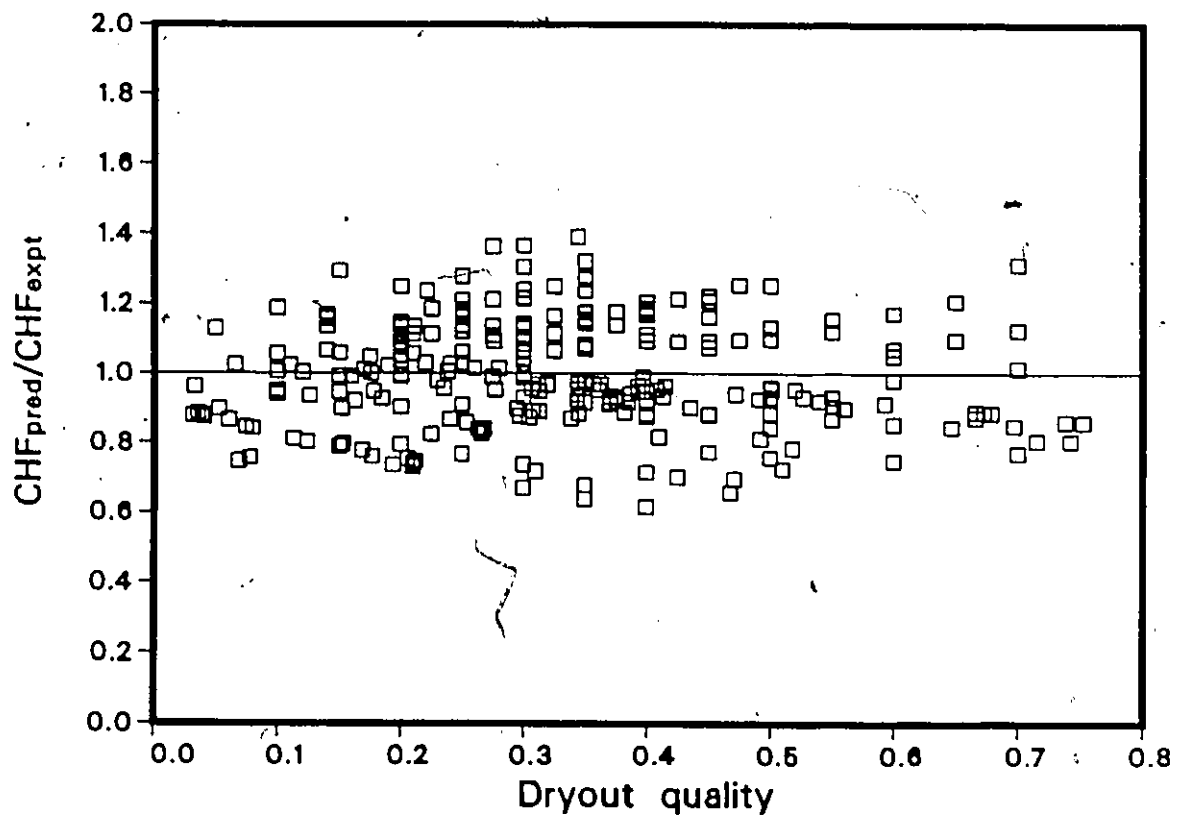


Figure 42. Comparison of Predicted and Experimental CHF for Water using Eq. 6.9.

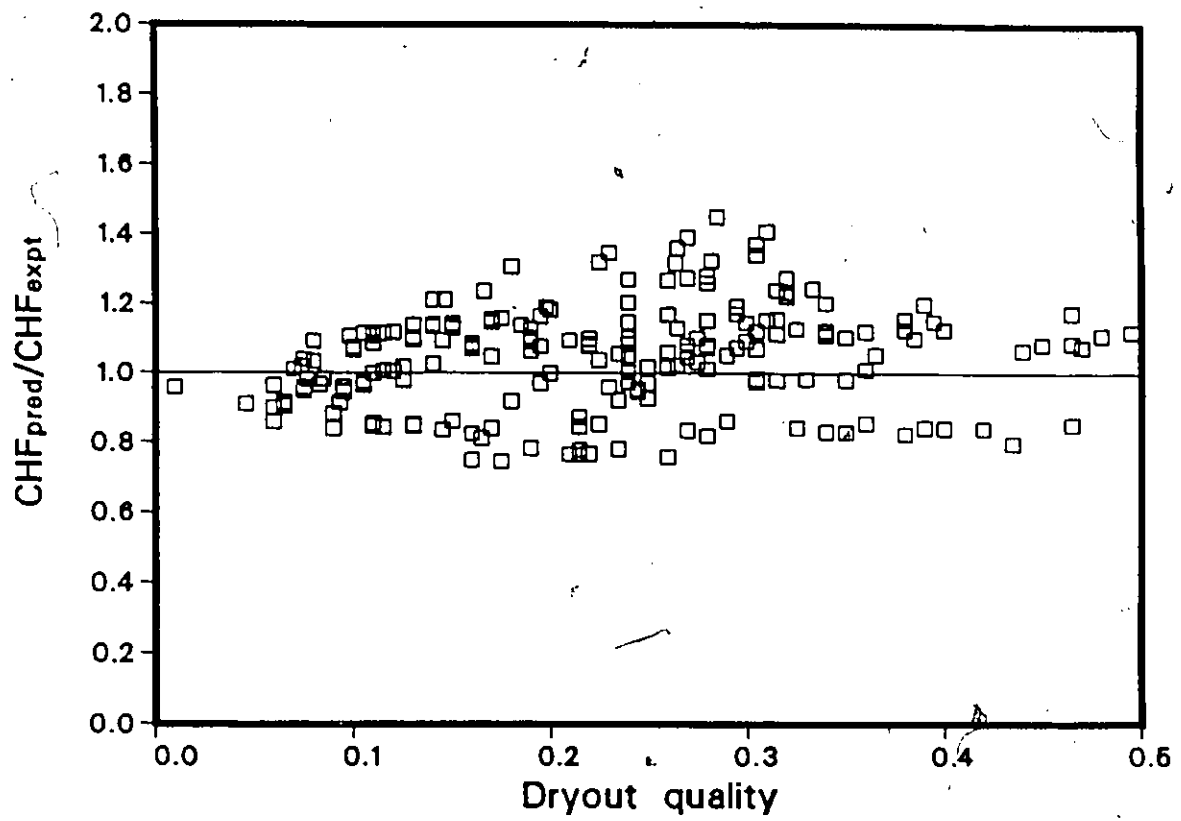


Figure 43. Comparison of Predicted and Experimental CHF for Freon-12 using Eq. 6.9.

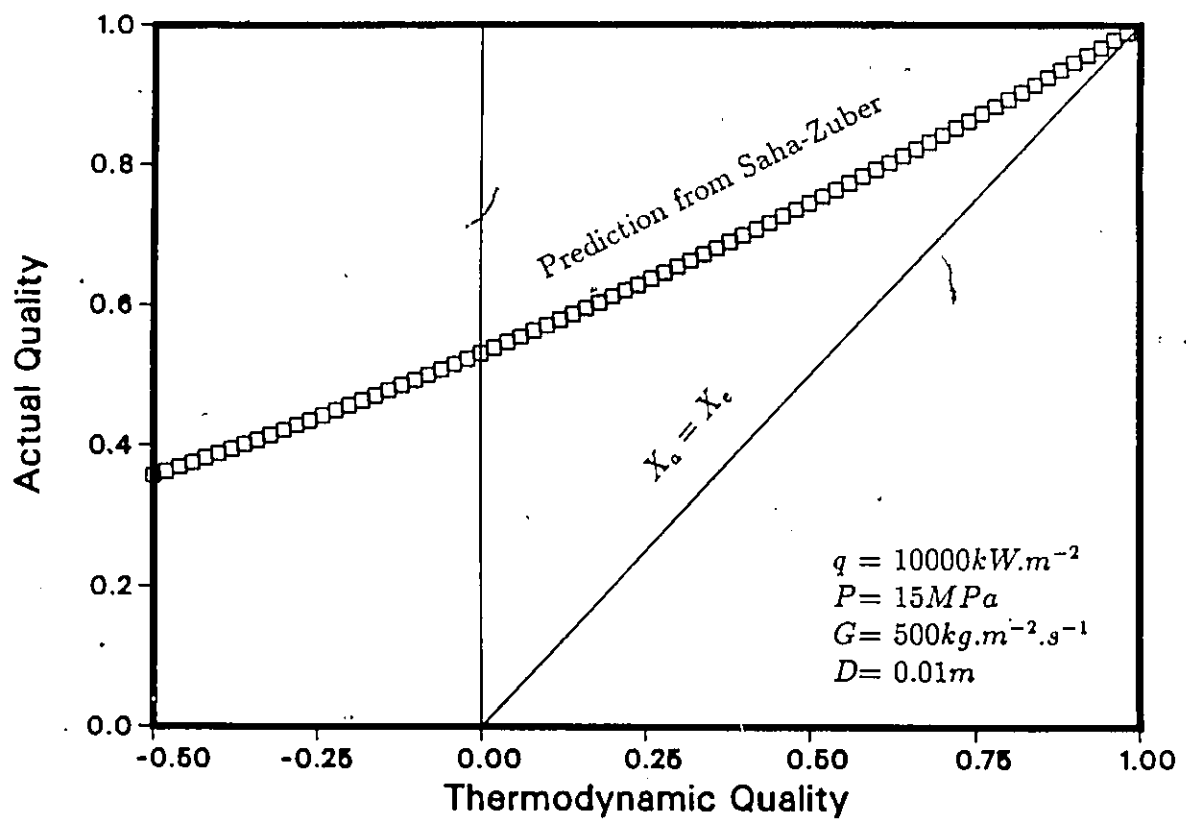


Figure 44. Actual Quality as Predicted by Saha-Zuber's Correlation (High Pressure and High Heat Flux).

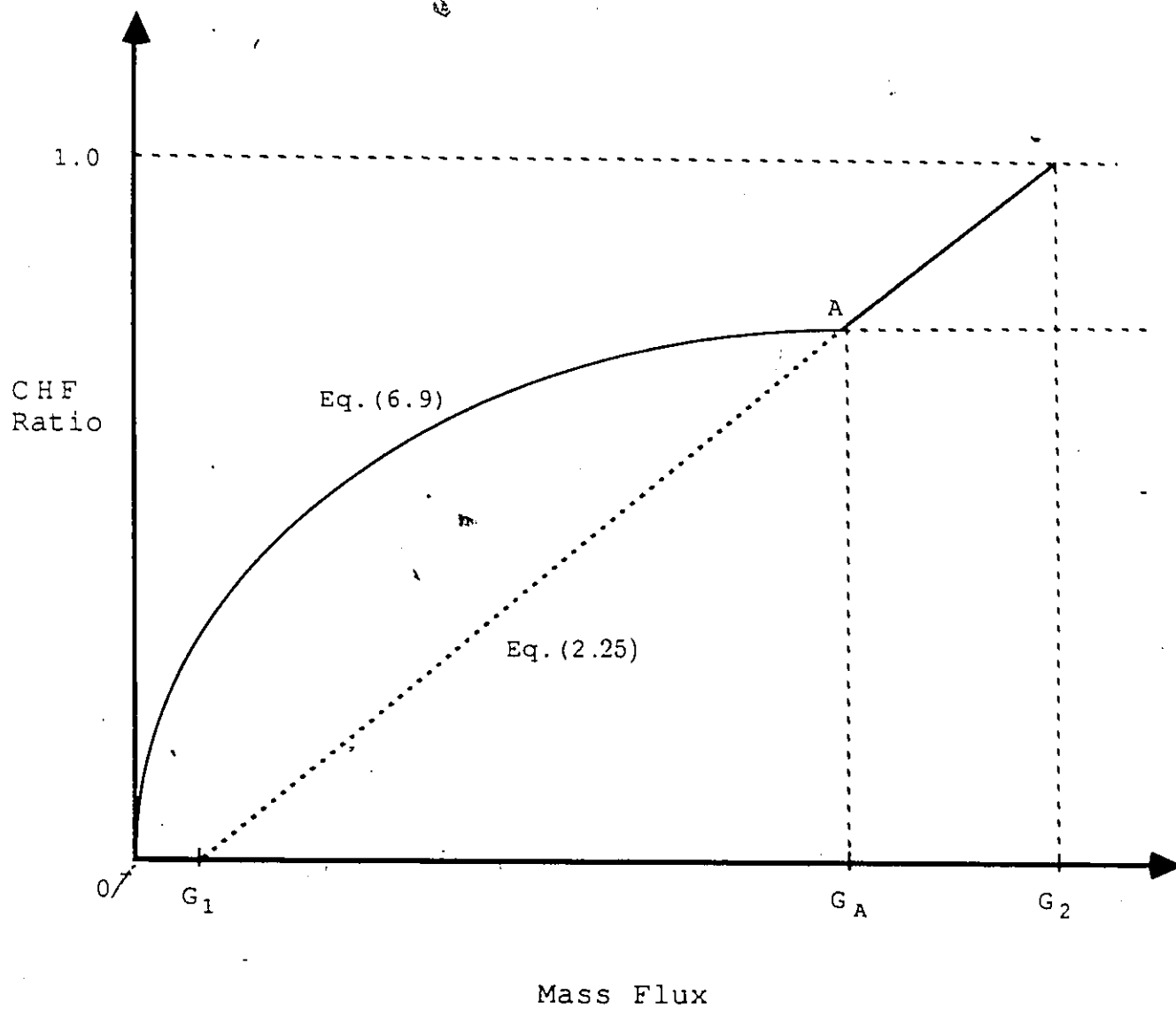


Figure 45. CHF Ratio Prediction as a Function of Mass Flux.

Appendix A

CHF DATA BANK

Data for CHF in horizontal tubes were obtained from Merilo (1977), Merilo and Ahmad (1979), Robertson (1973), Becker (1971), Leontiev et al. (1981), Lis and Strickland (1970), Kohler and Hein (1986) Wang and Su (1980), Rounthwaite (1968) and Ishigai et al. (1970a). Most CHF data for vertical tubes were taken from the table look-up method (Groeneveld et al., 1986a) and whenever possible, experimental data were recorded. The data index for CHF_{ver} is 1 for experimental data and 2 for value taken from table look-up method. Table A-1 shows the data bank tabulated into groups according to fluids (water or Freon-12), sources of experiments and heated length. Within each group, the data are arranged into columns of mass flux ($G, kg.m^{-2}.s^{-1}$), critical quality (X_{cr}), pressure (P, MPa), tube diameter (D, m), CHF_{hor} ($kW.m^{-2}$), CHF_{ver} ($kW.m^{-2}$) and data index. The quantities tabulated are explained below:

- | | |
|----------------|---|
| 1) L_h/D | Heated length over tube diameter ratio |
| 2) G | mass flux ($kg.m^{-2}.s^{-1}$) |
| 3) X_{cr} | Quality at critical heat flux |
| 4) P | Pressure (MPa) |
| 5) D | Tube diameter (m) |
| 6) CHF_{hor} | critical heat flux for horizontal tube
flow obtained from experiment ($kW.m^{-2}$) |
| 7) CHF_{ver} | critical heat flux for vertical flow ($kW.m^{-2}$) |

- a.
- 8) $CHFR$ critical heat flux ratio, CHF_{hor}/CHF_{ver}
9) I data index for CHF_{ver}
1—experimental
2—table look-up method

Some of the horizontal CHF data were much greater than the corresponding vertical CHF data. This is not likely to be correct from the consideration of physical mechanisms involved in horizontal CHF. The discrepancies could be due to experimental uncertainties or the inaccuracies in predicting the vertical CHF's for certain flow conditions.. Those data for which $CHFR > 1.3$ were screened because they are not considered to be correct.

Table A-1 Data Bank for  in Horizontal Flow

Fluid: Water

Source: Robertson (1973)

G ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	X_{cr}	P (MPa)	D (m)	$L_H/D = 160$			I
				CHF _{hor} ($\text{kW}\cdot\text{m}^{-2}$)	CHF _{ver} ($\text{kW}\cdot\text{m}^{-2}$)	CHFR	
680.	0.1760	6.8900	0.01900	1129.	3311.	0.34098	2
680.	0.1900	6.8900	0.01900	807.	3120.	0.25865	2
680.	0.2000	6.8900	0.01900	746.	2961.	0.25194	2
680.	0.2500	6.8900	0.01900	684.	2887.	0.23692	2
680.	0.3000	6.8900	0.01900	651.	2465.	0.26410	2
680.	0.3500	6.8900	0.01900	667.	2285.	0.29190	2
680.	0.4000	6.8900	0.01900	701.	2106.	0.33286	2
680.	0.4500	6.8900	0.01900	718.	1979.	0.36281	2
1000.	0.2000	6.8900	0.01900	1026.	2678.	0.38312	2
1000.	0.2100	6.8900	0.01900	961.	2650.	0.36264	2
1000.	0.2210	6.8900	0.01900	930.	2619.	0.35510	2
1000.	0.2500	6.8900	0.01900	1009.	2536.	0.39787	2
1000.	0.2750	6.8900	0.01900	1043.	2529.	0.41242	2
1000.	0.3000	6.8900	0.01900	1026.	2521.	0.40698	2
1000.	0.3500	6.8900	0.01900	1002.	2396.	0.41820	2
1360.	0.1600	6.8900	0.01900	1303.	2910.	0.44777	2
1360.	0.1750	6.8900	0.01900	1238.	2833.	0.43699	2
1360.	0.2000	6.8900	0.01900	1173.	2684.	0.43703	2
1360.	0.2250	6.8900	0.01900	1129.	2607.	0.43306	2
1360.	0.2500	6.8900	0.01900	1119.	2530.	0.44229	2
1360.	0.2750	6.8900	0.01900	1061.	2430.	0.43663	2
1360.	0.3000	6.8900	0.01900	1026.	2329.	0.44053	2
1360.	0.3250	6.8900	0.01900	958.	2205.	0.43447	2
1360.	0.3500	6.8900	0.01900	855.	2081.	0.41086	2

Table A-1. (Cont'd)
Fluid: Water
Source: Robertson (1973)

$L_h/D = 160$							
G ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	X_{cr}	P (MPa)	D (m)	CHF_{hor} ($\text{kW}\cdot\text{m}^{-2}$)	CHF_{ver} ($\text{kW}\cdot\text{m}^{-2}$)	$CHFR$	I
680.	0.4000	3.4000	0.01900	1386.	3605.	0.38447	2
680.	0.4250	3.4000	0.01900	1351.	3370.	0.40089	2
680.	0.4500	3.4000	0.01900	1300.	3135.	0.41467	2
680.	0.4750	3.4000	0.01900	1262.	2900.	0.43517	2
680.	0.5000	3.4000	0.01900	1225.	2670.	0.45880	2
680.	0.5500	3.4000	0.01900	1105.	2437.	0.45343	2
680.	0.2250	5.2000	0.01900	1225.	3214.	0.38115	2
680.	0.2500	5.2000	0.01900	1122.	3181.	0.35272	2
680.	0.3000	5.2000	0.01900	1009.	2896.	0.34841	2
680.	0.3250	5.2000	0.01900	975.	2823.	0.34538	2
680.	0.3500	5.2000	0.01900	924.	2749.	0.33612	2
680.	0.3750	5.2000	0.01900	907.	2676.	0.33894	2
1000.	0.2380	5.2000	0.01900	1368.	2989.	0.45768	2
1000.	0.2500	5.2000	0.01900	1266.	2965.	0.42698	2
1000.	0.2750	5.2000	0.01900	1129.	2939.	0.38414	2
1000.	0.3000	5.2000	0.01900	1112.	2913.	0.38174	2
1000.	0.3500	5.2000	0.01900	1177.	2820.	0.41738	2
$L_h/D = 239$							
1360.	0.2250	6.8900	0.01270	1471.	2942.	0.50000	1
1360.	0.2500	6.8900	0.01270	1420.	2874.	0.49408	1
1360.	0.2750	6.8900	0.01270	1351.	2805.	0.48164	1
1360.	0.3000	6.8900	0.01270	1283.	2709.	0.47361	1
1360.	0.3250	6.8900	0.01270	1197.	2641.	0.45324	1
1360.	0.3500	6.8900	0.01270	1129.	2504.	0.45088	1
1360.	0.3750	6.8900	0.01270	1078.	2429.	0.44380	1
1360.	0.4000	6.8900	0.01270	1009.	2291.	0.44042	1
1360.	0.4250	6.8900	0.01270	917.	2172.	0.42219	1
1360.	0.4500	6.8900	0.01270	855.	2053.	0.41646	1
1360.	0.4750	6.8900	0.01270	766.	1950.	0.39282	1

Table A-1 (Continue)
Fluid: Water
Source: Leontiev et al. (1981)
 $L_h/D = 75$

G ($\text{kg.m}^{-2}.\text{s}^{-1}$)	X_{cr}	P (MPa)	D (m)	CHF_{hor} (kW.m^{-2})	CHF_{ver} (kW.m^{-2})	$CHFR$	I
2000.	0.0660	13.7300	0.00600	2400.	2530.	0.94862	1
2000.	0.1000	13.7300	0.00600	1900.	2150.	0.88372	1
2000.	0.1100	13.7300	0.00600	1950.	2090.	0.93301	1
2000.	0.2100	13.7300	0.00600	1100.	1210.	0.90909	1
2000.	0.2300	13.7300	0.00600	1150.	1160.	0.99138	1
2000.	0.2500	13.7300	0.00600	800.	881.	0.90806	1
1000.	0.2060	6.8600	0.00600	4150.	4400.	0.94318	1
1000.	0.3100	6.8600	0.00600	3600.	3850.	0.93506	1
1000.	0.4100	6.8600	0.00600	2900.	3250.	0.89231	1
1000.	0.5200	6.8600	0.00600	2050.	2640.	0.77652	1
1000.	0.5400	6.8600	0.00600	2100.	2420.	0.86777	1
2000.	0.1260	6.8600	0.00600	4450.	3905.	1.13956	2
2000.	0.1780	6.8600	0.00600	3870.	3622.	1.06847	2
2000.	0.2000	6.8600	0.00600	3163.	3575.	0.88476	2
2000.	0.2110	6.8600	0.00600	2900.	3510.	0.82621	2
2000.	0.3000	6.8600	0.00600	2207.	2737.	0.80636	2
2000.	0.0330	9.8100	0.00600	4400.	4050.	1.08642	2
2000.	0.1000	9.8100	0.00600	3696.	3111.	1.18804	2
2000.	0.1520	9.8100	0.00600	3250.	2456.	1.32329	2
2000.	0.1630	9.8100	0.00600	2870.	2362.	1.21507	2
2000.	0.1850	9.8100	0.00600	2543.	2176.	1.16866	2
2000.	0.2350	9.8100	0.00600	2000.	1858.	1.07643	2
2000.	0.2760	9.8100	0.00600	1380.	1598.	0.86358	2

Table A-1 (Continue)

Fluid: Water

Source: Becker (1971)

$L_h/D = 96.5$							
G ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	X_{cr}	P (MPa)	D (m)	CHF_{hor} ($\text{kW}\cdot\text{m}^{-2}$)	CHF_{ver} ($\text{kW}\cdot\text{m}^{-2}$)	$CHFR$	I
238.	0.0530	3.0000	0.00995	1064.	6275.	0.16956	2
248.	0.0320	3.0000	0.00995	1083.	6339.	0.17085	2
358.	0.7150	3.0000	0.00995	1893.	2487.	0.76116	2
365.	0.7420	3.0000	0.00995	1920.	2190.	0.87671	2
477.	0.6470	3.0000	0.00995	2283.	3108.	0.73456	2
601.	0.5600	3.0000	0.00995	2562.	3370.	0.76024	2
610.	0.5510	3.0000	0.00995	2586.	3394.	0.76193	2
758.	0.4910	3.0000	0.00995	2992.	3452.	0.86674	2
772.	0.4720	3.0000	0.00995	2992.	3681.	0.81282	2
980.	0.4130	3.0000	0.00995	3381.	3809.	0.88763	2
1010.	0.4350	3.0000	0.00995	3506.	3566.	0.98317	2
1454.	0.3130	2.9400	0.00995	4074.	4127.	0.98716	2
1513.	0.3050	3.1400	0.00995	4074.	4090.	0.99609	2
1518.	0.3080	2.8700	0.00995	4088.	4102.	0.99171	2
1557.	0.2970	3.1400	0.00995	4136.	4121.	1.00364	2
1590.	0.2950	2.8600	0.00995	4136.	4157.	0.99495	2
216.	0.0360	1.9500	0.00995	757.	6138.	0.12333	2
212.	0.1500	2.1100	0.00995	1071.	5609.	0.19094	2
226.	0.1240	1.9600	0.00995	1072.	5726.	0.18722	2
233.	0.0410	2.0600	0.00995	1014.	6171.	0.16432	2
234.	0.0390	1.9100	0.00995	991.	6112.	0.16214	2
246.	0.1690	2.0600	0.00995	1366.	5468.	0.24982	2
247.	0.0610	1.9900	0.00995	1341.	6098.	0.21991	2
354.	0.7520	2.1400	0.00995	1884.	1941.	0.97063	2
365.	0.7380	2.0400	0.00995	1947.	2070.	0.94058	2
473.	0.6730	2.0400	0.00995	2279.	2651.	0.85968	2
476.	0.6790	1.9900	0.00995	2302.	2554.	0.90133	2
494.	0.6660	1.9400	0.00995	2355.	2616.	0.90023	2
597.	0.5930	1.9300	0.00995	2563.	2939.	0.87207	2

Table A-1 (Continue)
 Fluid: Water
 Source: Becker (1971)

$L_H/D = 96.5$							
G ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	X_{cr}	P (MPa)	D (m)	CHF_{hor} ($\text{kW}\cdot\text{m}^{-2}$)	CHF_{ver} ($\text{kW}\cdot\text{m}^{-2}$)	$CHFR$	I
746.	0.5270	1.9100	0.00995	2863.	2940.	0.97381	2
763.	0.5010	2.0700	0.00995	2909.	3298.	0.88205	2
1058.	0.3970	1.9900	0.00995	3418.	3898.	0.87686	2
1072.	0.4150	1.9700	0.00995	3484.	3594.	0.96939	2
1498.	0.3200	2.0600	0.00995	3976.	4019.	0.98930	2
1511.	0.3190	2.1100	0.00995	4004.	4015.	0.99726	2
1544.	0.3130	2.1100	0.00995	4071.	4060.	1.00271	2
1572.	0.3120	1.9600	0.00995	4031.	4042.	0.99728	2
1590.	0.3070	1.9300	0.00995	4086.	4089.	0.99927	2
1742.	0.2770	1.9400	0.00995	4072.	4110.	0.99075	2
161.	0.1530	0.9300	0.00995	753.	3999.	0.18830	2
183.	0.1130	0.9900	0.00995	788.	4856.	0.16227	2
187.	0.0800	1.0400	0.00995	750.	5134.	0.14608	2
197.	0.0750	1.0300	0.00995	783.	5282.	0.14824	2
188.	0.2120	1.0800	0.00995	1024.	4566.	0.22427	2
198.	0.2100	0.9500	0.00995	1048.	4272.	0.24532	2
202.	0.1770	1.0500	0.00995	1023.	4898.	0.20886	2
252.	0.2100	1.1300	0.00995	1364.	4735.	0.28807	2
268.	0.1940	0.9600	0.00995	1360.	4463.	0.30473	2
371.	0.6970	1.1500	0.00995	1854.	1534.	1.20860	2
394.	0.6660	1.1000	0.00995	1904.	1723.	1.10505	2
1157.	0.3760	1.0800	0.00995	3320.	2923.	1.13582	2
1168.	0.3710	1.0800	0.00995	3358.	2966.	1.13216	2
1175.	0.3700	0.9800	0.00995	3295.	2747.	1.19949	2
1177.	0.3850	1.1000	0.00995	3377.	2828.	1.19413	2
1208.	0.3700	1.1000	0.00995	3377.	2960.	1.14088	2

Table A-1 (Continue)

Fluid: Water

Source: Becker (1971)

$L_h/D = 74.4$							
G ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	X_{cr}	P (MPa)	D (m)	CHF_{hor} ($\text{kW}\cdot\text{m}^{-2}$)	CHF_{ver} ($\text{kW}\cdot\text{m}^{-2}$)	$CHFR$	l
480.	0.4710	3.0400	0.01290	2411.	3963.	0.60838	2
495.	0.4680	2.9400	0.01290	2501.	4017.	0.62260	2
706.	0.3820	3.0900	0.01290	2919.	4444.	0.65684	2
729.	0.3760	2.9700	0.01290	2959.	4536.	0.65234	2
738.	0.3700	3.0400	0.01290	2980.	4546.	0.65552	2
948.	0.3390	3.0900	0.01290	3442.	4231.	0.81352	2
966.	0.3450	2.8900	0.01290	3515.	4194.	0.83810	2
1363.	0.2680	2.8900	0.01290	3963.	4179.	0.94831	2
1372.	0.2660	3.0400	0.01290	3977.	4148.	0.95878	2
1420.	0.2660	2.8900	0.01290	4019.	4078.	0.98553	2
350.	0.0780	1.9600	0.01290	2055.	5593.	0.36742	2
362.	0.0690	1.9600	0.01290	2034.	5596.	0.36347	2
475.	0.5100	1.9600	0.01290	2463.	3741.	0.65838	2
482.	0.5180	1.9100	0.01290	2440.	3669.	0.66503	2
507.	0.4920	1.9600	0.01290	2488.	3835.	0.64876	2
723.	0.4080	1.8800	0.01290	2941.	4207.	0.69907	2
741.	0.3970	2.0900	0.01290	2970.	4444.	0.66832	2
752.	0.3930	1.9300	0.01290	3004.	4372.	0.68710	2
966.	0.3630	1.9600	0.01290	3383.	4136.	0.81794	2
977.	0.3610	2.0900	0.01290	3488.	4166.	0.83725	2
994.	0.3570	1.9800	0.01290	3482.	4193.	0.83043	2
1020.	0.3570	1.9600	0.01290	3488.	4129.	0.84476	2
1533.	0.2630	2.0600	0.01290	3969.	3952.	1.00430	2
1581.	0.2540	1.9600	0.01290	3969.	3942.	1.00685	2
1662.	0.2400	2.1100	0.01290	4023.	3923.	1.02549	2
795.	0.3930	1.0500	0.01290	2913.	3308.	0.88059	2
816.	0.3860	1.1300	0.01290	2976.	3372.	0.88256	2

Table A-1 (Continue)
 Fluid: Water (Subcooled Data)
 Source: Becker (1971)

$L_h/D = 74.4$							
G ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	X_{cr}	P (MPa)	D (m)	CHF_{hor} ($\text{kW}\cdot\text{m}^{-2}$)	CHF_{ver} ($\text{kW}\cdot\text{m}^{-2}$)	$CHFR$	I
325.	-0.2790	2.9400	0.01290	1499.	6687.	0.22418	2
329.	-0.2790	3.0400	0.01290	1526.	6678.	0.22851	2
331.	-0.2830	2.9400	0.01290	1536.	6704.	0.22911	2
342.	-0.2900	3.0400	0.01290	1559.	6718.	0.23205	2
374.	-0.0210	3.1400	0.01290	2013.	6242.	0.32248	2
387.	-0.0210	3.1200	0.01290	2004.	6285.	0.31887	2
310.	-0.2240	2.0600	0.01290	1477.	6495.	0.22740	2
317.	-0.2180	2.1100	0.01290	1561.	6479.	0.24093	2
318.	-0.2120	1.9600	0.01290	1535.	6446.	0.23812	2
$L_h/D = 96.5$							
228.	-0.1210	3.0800	0.00995	758.	6697.	0.11318	2
259.	-0.0520	2.9400	0.00995	1021.	6659.	0.15332	2
270.	-0.0830	3.0400	0.00995	999.	6755.	0.14789	2

Table A-1 (Continue)

Fluid: Water

Source: Merilo (1977)

$L_h/D = 194.0$							
G ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	X_{cr}	P (MPa)	D (m)	CHF_{hor} ($\text{kW}\cdot\text{m}^{-2}$)	CHF_{ver} ($\text{kW}\cdot\text{m}^{-2}$)	CHFR	I
950.	0.4000	6.8900	0.01260	1080.	2588.	0.41731	2
950.	0.4500	6.8900	0.01260	1004.	2347.	0.42778	2
1360.	0.2500	6.8900	0.01260	1370.	2901.	0.47225	2
1360.	0.3000	6.8900	0.01260	1190.	2671.	0.44553	2
1360.	0.3500	6.8900	0.01260	1070.	2387.	0.44826	2
950.	0.3000	9.6500	0.01260	895.	1778.	0.50337	2
950.	0.3500	9.6500	0.01260	803.	1488.	0.53965	2
$L_h/D = 290$							
950.	0.5000	6.8900	0.01260	928.	2106.	0.44065	2
950.	0.5500	6.8900	0.01260	853.	1878.	0.45421	2
950.	0.6000	6.8900	0.01260	777.	1650.	0.47091	2
1360.	0.4000	6.8900	0.01260	970.	2103.	0.46125	2
1360.	0.4500	6.8900	0.01260	870.	1831.	0.47515	2
3800.	0.2000	6.8900	0.01260	2020.	2158.	0.93605	1
3800.	0.2200	6.8900	0.01260	1980.	2080.	0.95192	1
3800.	0.2400	6.8900	0.01260	1880.	2000.	0.94000	1
3800.	0.2600	6.8900	0.01260	1770.	1920.	0.92187	1
950.	0.4000	9.6500	0.01260	724.	1198.	0.60434	2
950.	0.4500	9.6500	0.01260	671.	1069.	0.62769	2
3800.	0.1200	9.6500	0.01260	1824.	1838.	0.99238	2
3800.	0.1500	9.6500	0.01260	1618.	1750.	0.92457	1
3800.	0.1700	9.6500	0.01260	1474.	1650.	0.89333	1
5700.	0.1000	9.6500	0.01260	1960.	1965.	0.99746	1

Table A-1 (Continue)

Fluid: Water

Source: Merilo (1977)

$L_h/D = 387.0$							
G ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	X_{cr}	P (MPa)	D (m)	CHF_{hor} ($\text{kW}\cdot\text{m}^{-2}$)	CHF_{ver} ($\text{kW}\cdot\text{m}^{-2}$)	$CHFR$	I
950.	0.6500	6.8900	0.01260	701.	1210.	0.57934	1
950.	0.7000	6.8900	0.01260	625.	882.	0.70862	1
1360.	0.5000	6.8900	0.01260	715.	1574.	0.45426	1
3800.	0.2800	6.8900	0.01260	1620.	1816.	0.89207	1
3800.	0.3000	6.8900	0.01260	1375.	1697.	0.81025	1
950.	0.5000	9.6500	0.01260	632.	1150.	0.54957	1
950.	0.5500	9.6500	0.01260	574.	789.	0.72750	1
950.	0.6000	9.6500	0.01260	538.	550.	0.97818	1
3800.	0.2000	9.6500	0.01260	1395.	1600.	0.87187	1
3800.	0.2500	9.6500	0.01260	1158.	1500.	0.77200	1
5700.	0.1500	9.6500	0.01260	1842.	1850.	0.99568	1
5700.	0.2000	9.6500	0.01260	1782.	1785.	0.99832	1

Table A-1 (Continue)
Fluid: Water
Source: Kohler and Hein (1986)

$L_H/D = 488.0$							
G ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	X_{cr}	P (MPa)	D (m)	CHF_{hor} ($\text{kW}\cdot\text{m}^{-2}$)	CHF_{ver} ($\text{kW}\cdot\text{m}^{-2}$)	$CHFR$	l
500.	0.0500	15.0000	0.01250	283.	1810.	0.15635	2
500.	0.1000	15.0000	0.01250	240.	1810.	0.13260	2
500.	0.1500	15.0000	0.01250	205.	1767.	0.11602	2
500.	0.2000	15.0000	0.01250	195.	1413.	0.13800	2
500.	0.2500	15.0000	0.01250	182.	1365.	0.13333	2
500.	0.3000	15.0000	0.01250	169.	1120.	0.15089	2
500.	0.3500	15.0000	0.01250	155.	1032.	0.15019	2
500.	0.4000	15.0000	0.01250	155.	945.	0.16402	2
1000.	0.1500	15.0000	0.01250	385.	1263.	0.30483	2
1000.	0.2000	15.0000	0.01250	346.	1059.	0.32672	2
1000.	0.2500	15.0000	0.01250	311.	955.	0.32565	2
1000.	0.3000	15.0000	0.01250	277.	801.	0.34560	2
1000.	0.3500	15.0000	0.01250	248.	584.	0.42466	2
1000.	0.4000	15.0000	0.01250	224.	366.	0.61202	2
2500.	0.2750	15.0000	0.01250	569.	592.	0.96115	2
2500.	0.3000	15.0000	0.01250	446.	501.	0.89022	2
2500.	0.3250	15.0000	0.01250	380.	454.	0.83700	2
2500.	0.3500	15.0000	0.01250	339.	408.	0.83088	2

Table A-1 (Continue)
Fluid: Water
Source: Kohler and Hein (1986)

$L_h/D = 251.0$							
G ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	X_{cr}	P (MPa)	D (m)	CHF_{br} ($\text{kW}\cdot\text{m}^{-2}$)	CHF_{ver} ($\text{kW}\cdot\text{m}^{-2}$)	$CHFR$	I
500.	0.1400	10.0000	0.02430	332.	2649.	0.12533	2
750.	0.1400	10.0000	0.02430	436.	2561.	0.17025	2
1000.	0.1400	10.0000	0.02430	529.	2518.	0.21009	2
1500.	0.1400	10.0000	0.02430	600.	2216.	0.27076	2
500.	0.3440	10.0000	0.02430	209.	1817.	0.11502	2
750.	0.3440	10.0000	0.02430	440.	1537.	0.28627	2
1000.	0.3440	10.0000	0.02430	485.	1490.	0.40756	2
1500.	0.3440	10.0000	0.02430	575.	983.	0.58494	2
2500.	0.3440	10.0000	0.02430	592.	735.	0.80544	2
1500.	0.1000	15.0000	0.02430	477.	1229.	0.38812	2
1500.	0.2000	15.0000	0.02430	446.	819.	0.54457	2
1500.	0.3000	15.0000	0.02430	422.	511.	0.82583	2
1500.	0.4000	15.0000	0.02430	323.	265.	1.21887	2
1500.	0.3500	15.0000	0.02430	405.	386.	1.04922	2
1500.	0.4250	15.0000	0.02430	200.	243.	0.82305	2
2500.	0.2500	15.0000	0.02430	600.	630.	0.95238	2
2500.	0.3000	15.0000	0.02430	500.	462.	1.08225	2
2500.	0.3500	15.0000	0.02430	400.	376.	1.06383	2
2500.	0.4000	15.0000	0.02430	300.	290.	1.03448	2
2500.	0.4500	15.0000	0.02430	223.	246.	0.90650	2
750.	0.2000	10.0000	0.02430	444.	2278.	0.19491	2
750.	0.3000	10.0000	0.02430	440.	1695.	0.25959	2
750.	0.4000	10.0000	0.02430	430.	1336.	0.32186	2
750.	0.5000	10.0000	0.02430	398.	1082.	0.36784	2
750.	0.6000	10.0000	0.02430	331.	879.	0.37656	2
750.	0.7000	10.0000	0.02430	243.	616.	0.39448	2

Table A-1 (Continue)
Fluid: Water
Source: Kohler and Hein (1986)

$L_h/D = 251.0$						
G ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	X_{cr}	P (MPa)	D (m)	CHF_{hor} ($\text{kW}\cdot\text{m}^{-2}$)	CHF_{ver} ($\text{kW}\cdot\text{m}^{-2}$)	$CHFR$
1000.	0.1000	10.0000	0.02430	523.	2680.	0.19515
1000.	0.2000	10.0000	0.02430	525.	2244.	0.23396
1000.	0.3000	10.0000	0.02430	500.	1464.	0.34153
1000.	0.4000	10.0000	0.02430	458.	842.	0.54394
1000.	0.5000	10.0000	0.02430	412.	643.	0.64075
1000.	0.6000	10.0000	0.02430	350.	472.	0.74153
1000.	0.7000	10.0000	0.02430	255.	314.	0.81210
1500.	0.2000	10.0000	0.02430	569.	1749.	0.32533
1500.	0.3000	10.0000	0.02430	538.	1213.	0.44353
1500.	0.4000	10.0000	0.02430	500.	691.	0.72359
1500.	0.5000	10.0000	0.02430	288.	437.	0.65904
1500.	0.6000	10.0000	0.02430	210.	301.	0.69767
2500.	0.2500	20.0000	0.02430	531.	856.	0.62033
2500.	0.3000	20.0000	0.02430	446.	712.	0.62640
2500.	0.3500	20.0000	0.02430	400.	628.	0.63694
2500.	0.4000	20.0000	0.02430	294.	543.	0.54144
1000.	0.4500	10.0000	0.02430	459.	806.	0.56948
1000.	0.5000	10.0000	0.02430	354.	698.	0.50716
1000.	0.5500	10.0000	0.02430	280.	605.	0.46281
1000.	0.6000	10.0000	0.02430	212.	513.	0.41326
1000.	0.6500	10.0000	0.02430	175.	427.	0.40984
1000.	0.7000	10.0000	0.02430	150.	340.	0.44118

Table A-1 (Continue)
 Fluid: Water
 Source: Rounthwaite (1968)

$L_h/D = 280.0$							
G ($\text{kg.m}^{-2}.\text{s}^{-1}$)	X_{cr}	P (MPa)	D (m)	CHF_{hor} (kW.m^{-2})	CHF_{ver} (kW.m^{-2})	$CHFR$	I
94.	0.0400	1.4800	0.04130	63.	3483.	0.01811	2
141.	0.0700	1.4800	0.04130	63.	4035.	0.01564	2
188.	0.1300	1.4800	0.04130	63.	4470.	0.01412	2
188.	0.9400	1.4800	0.04130	66.	378.	0.17421	2
155.	0.9300	2.8600	0.04130	63.	440.	0.14216	2
155.	0.9380	2.8600	0.04130	51.	390.	0.12999	2
155.	0.9550	2.8600	0.04130	37.	283.	0.13247	2
155.	0.9850	2.8600	0.04130	25.	94.	0.26600	2
214.	0.8900	2.8600	0.04130	63.	711.	0.08806	2
214.	0.9150	2.8600	0.04130	51.	567.	0.08938	2
214.	0.9250	2.8600	0.04130	37.	501.	0.07492	2
214.	0.9500	2.8600	0.04130	25.	334.	0.07522	2

Table A-1 (Continue)
Fluid: Water
Source: Lis and Strickland (1970)

$L_h/D = 73.2$							
G ($\text{kg.m}^{-2}.\text{s}^{-1}$)	X_{cr}	P (MPa)	D (m)	CHF_{hor} (kW.m^{-2})	CHF_{ver} (kW.m^{-2})	$CHFR$	l
90.	0.0100	1.5000	0.04100	63.	3746.	0.01682	2
195.	0.1000	1.5000	0.04100	63.	4703.	0.01340	2
300.	0.1000	3.5500	0.04100	63.	5090.	0.01238	2
480.	0.2000	3.5500	0.04100	63.	4390.	0.01435	2
480.	0.0950	5.2500	0.04100	63.	4413.	0.01428	2
590.	0.2100	5.2500	0.04100	63.	3544.	0.01778	2
480.	0.0700	6.6500	0.04100	63.	4395.	0.01433	2
580.	0.0900	6.6500	0.04100	63.	4343.	0.01450	2
700.	0.1500	6.6500	0.04100	63.	3961.	0.01590	2
940.	0.0400	3.5500	0.04100	63.	5299.	0.01189	2

Table A-1 (Continue)
Fluid: Water
Source: Wang and Su (1980)

$L_h/D = 167.0$							
G ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	X_{cr}	P (MPa)	D (m)	CHF_{hor} ($\text{kW}\cdot\text{m}^{-2}$)	CHF_{ver} ($\text{kW}\cdot\text{m}^{-2}$)	$CHFR$	I
490.	0.8500	4.9000	0.01200	700.	1268.	0.55210	2
490.	0.8900	4.9000	0.01200	600.	1059.	0.56681	2
490.	0.9200	4.9000	0.01200	500.	805.	0.62113	2
490.	0.9400	4.9000	0.01200	400.	604.	0.66254	2
490.	0.9500	4.9000	0.01200	350.	503.	0.69566	2
490.	0.9600	4.9000	0.01200	300.	402.	0.74535	2
490.	0.9650	4.9000	0.01200	250.	352.	0.70986	2
490.	0.9700	4.9000	0.01200	200.	302.	0.66254	2
490.	0.9750	4.9000	0.01200	150.	252.	0.59628	2
490.	0.9800	4.9000	0.01200	100.	201.	0.49690	2
610.	0.8000	4.9000	0.01200	700.	1501.	0.46623	2
610.	0.8400	4.9000	0.01200	600.	1294.	0.46363	2
610.	0.8800	4.9000	0.01200	500.	1087.	0.46005	2
610.	0.9300	4.9000	0.01200	400.	688.	0.58119	2
610.	0.9500	4.9000	0.01200	350.	492.	0.71195	2
610.	0.9600	4.9000	0.01200	300.	393.	0.76281	2
610.	0.9700	4.9000	0.01200	250.	295.	0.84757	2
610.	0.9750	4.9000	0.01200	200.	246.	0.81366	2
610.	0.9800	4.9000	0.01200	150.	197.	0.76281	2
840.	0.7300	4.9000	0.01200	700.	1783.	0.39251	2
840.	0.7600	4.9000	0.01200	600.	1687.	0.35557	2
840.	0.7900	4.9000	0.01200	500.	1591.	0.31418	2
840.	0.8300	4.9000	0.01200	400.	1412.	0.28322	2
840.	0.8600	4.9000	0.01200	300.	1265.	0.23711	2
1100.	0.6500	4.9000	0.01200	600.	1874.	0.32019	2
1100.	0.7100	4.9000	0.01200	460.	1690.	0.27224	2
1100.	0.7600	4.9000	0.01200	370.	1672.	0.22135	2

Table A-1 (Continue)
Fluid: Water
Source: Ishigai et al. (1970a)

$L_h/D = 93.5$							
G ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	X_{cr}	P (MPa)	D (m)	CHF_{hor} ($\text{kW}\cdot\text{m}^{-2}$)	CHF_{ver} ($\text{kW}\cdot\text{m}^{-2}$)	$CHFR$	I
247.	0.597	0.12666	0.01070	1047.	1107.	0.94591	2
242.	0.706	0.12666	0.01070	1082.	893.	1.21111	2
240.	0.748	0.12666	0.01070	1105.	783.	1.41147	2
239.	0.736	0.12666	0.01070	1070.	813.	1.31576	2
238.	0.718	0.12666	0.01070	954.	861.	1.10801	2
238.	0.723	0.12666	0.01070	919.	846.	1.08559	2
199.	0.592	0.12666	0.01070	872.	1022.	0.85329	2
196.	0.662	0.12666	0.01070	872.	937.	0.93121	2
191.	0.761	0.12666	0.01070	884.	754.	1.17300	2
191.	0.793	0.12666	0.01070	837.	684.	1.22399	2
191.	0.762	0.12666	0.01070	756.	750.	1.00831	2
149.	0.575	0.12666	0.01070	640.	935.	0.68395	2
149.	0.678	0.12666	0.01070	721.	839.	0.85971	2
148.	0.687	0.12666	0.01070	698.	826.	0.84438	2
147.	0.725	0.12666	0.01070	709.	758.	0.93595	2
146.	0.762	0.12666	0.01070	709.	676.	1.04963	2
144.	0.788	0.12666	0.01070	686.	619.	1.10875	2
143.	0.814	0.12666	0.01070	698.	563.	1.23973	2
143.	0.553	0.12666	0.01070	465.	928.	0.50106	2
143.	0.729	0.12666	0.01070	581.	743.	0.78308	2
143.	0.807	0.12666	0.01070	640.	579.	1.10568	2
143.	0.796	0.12666	0.01070	605.	600.	1.00732	2
143.	0.847	0.12666	0.01070	640.	499.	1.28185	2
143.	0.775	0.12666	0.01070	570.	644.	0.88454	2
99.	0.816	0.12666	0.01070	570.	494.	1.15389	2
99.	0.853	0.12666	0.01070	581.	434.	1.34046	2
99.	0.795	0.12666	0.01070	547.	530.	1.03097	2
98.	0.857	0.12666	0.01070	558.	427.	1.30879	2

Table A-1 (Continue)
Fluid: Water
Source: Ishigai et al. (1970a)

$L_h/D = 93.5$							
G ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	X_{cr}	P (MPa)	D (m)	CHF_{hor} ($\text{kW}\cdot\text{m}^{-2}$)	CHF_{ver} ($\text{kW}\cdot\text{m}^{-2}$)	$CHFR$	l
96.	0.970	0.12666	0.01070	570.	107.	5.32992	2
96.	0.984	0.12666	0.01070	570.	59.	9.71968	2
95.	0.458	0.12666	0.01070	256.	868.	0.29477	2
95.	0.895	0.12666	0.01070	477.	366.	1.30409	2
95.	0.981	0.12666	0.01070	523.	67.	7.81639	2
95.	0.864	0.12666	0.01070	442.	412.	1.07382	2
95.	0.955	0.12666	0.01070	488.	160.	3.04612	2
$L_h/D = 50.3$							
397.	0.256	0.14692	0.00995	1746.	1477.	1.18222	2
380.	0.371	0.14692	0.00995	1396.	1364.	1.02329	2
380.	0.504	0.14692	0.00995	1744.	1275.	1.36866	2
299.	0.279	0.14692	0.00995	1454.	1388.	1.04708	2
288.	0.594	0.14692	0.00995	1977.	1128.	1.75341	2
285.	0.370	0.14692	0.00995	1105.	1281.	0.86156	2
285.	0.487	0.14692	0.00995	1221.	1218.	1.00266	2
198.	0.373	0.14692	0.00995	1105.	1114.	0.99207	2
191.	0.677	0.14692	0.00995	1454.	1007.	1.44331	2
190.	0.397	0.14692	0.00995	814.	1097.	0.74187	2
190.	0.487	0.14692	0.00995	814.	1067.	0.76318	2
1100.	0.588	0.14692	0.00995	814.	880.	0.92495	2
95.	0.980	0.14692	0.00995	1047.	82.	12.81772	2
95.	0.567	0.14692	0.00995	581.	875.	0.66461	2
95.	0.502	0.14692	0.00995	407.	878.	0.46342	2
$L_h/D = 121.0$							
798.	0.549	0.45596	0.00620	2791.	831.	3.35937	2
768.	0.626	0.45596	0.00620	2442.	694.	3.51942	2
738.	0.566	0.45596	0.00620	1861.	869.	2.14128	2
735.	0.542	0.45596	0.00620	1744.	933.	1.87000	2
598.	0.537	0.45596	0.00620	2035.	1378.	1.47686	2

Table A-1 (Continue)
Fluid: Water
Source: Ishigai et al. (1970a)

$L_h/D = 121.0$							
G ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	X_{cr}	P (MPa)	D (m)	CHF_{hor} ($\text{kW}\cdot\text{m}^{-2}$)	CHF_{ver} ($\text{kW}\cdot\text{m}^{-2}$)	$CHFR$	I
576.	0.684	0.45596	0.00620	1977.	593.	3.33231	2
554.	0.590	0.45596	0.00620	1454.	1195.	1.21643	2
551.	0.588	0.45596	0.00620	1396.	1208.	1.15519	2
398.	0.760	0.45596	0.00620	1744.	499.	3.49825	2
382.	0.813	0.45596	0.00620	1512.	398.	3.79449	2
368.	0.788	0.45596	0.00620	1279.	453.	2.82602	2
367.	0.598	0.45596	0.00620	930.	1573.	0.59131	2
$L_h/D = 89.6$							
796.	0.333	0.47623	0.00560	2675.	1865.	1.43420	2
787.	0.419	0.47623	0.00560	2791.	1426.	1.95777	2
779.	0.486	0.47623	0.00560	2907.	1090.	2.66753	2
766.	0.528	0.47623	0.00560	2849.	961.	2.96529	2
753.	0.545	0.47623	0.00560	2675.	932.	2.87114	2
742.	0.544	0.47623	0.00560	2500.	963.	2.59725	2
733.	0.480	0.47623	0.00560	1977.	1235.	1.60143	2
596.	0.368	0.47623	0.00560	2093.	2290.	0.91427	2
587.	0.409	0.47623	0.00560	1977.	2200.	0.89888	2
581.	0.512	0.47623	0.00560	2210.	1684.	1.31246	2
575.	0.652	0.47623	0.00560	2559.	825.	3.10113	2
563.	0.665	0.47623	0.00560	2384.	752.	3.17145	2
555.	0.634	0.47623	0.00560	2152.	959.	2.24439	2
550.	0.558	0.47623	0.00560	1686.	1487.	1.13376	2
393.	0.744	0.47623	0.00560	2152.	589.	3.65463	2
390.	0.606	0.47623	0.00560	1744.	1534.	1.13730	2
385.	0.733	0.47623	0.00560	1949.	637.	3.01159	2
382.	0.785	0.47623	0.00560	1977.	479.	4.12386	2
379.	0.708	0.47623	0.00560	1744.	723.	2.41140	2
374.	0.748	0.47623	0.00560	1744.	605.	2.88567	2
368.	0.763	0.47623	0.00560	1686.	565.	2.98251	2

Table A-1 (Continue)
Fluid: Water
Source: Ishigai et al. (1970a)

$L_h/D = 89.2$							
G ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	X_{cr}	P (MPa)	D (m)	CHF_{hor} ($\text{kW}\cdot\text{m}^{-2}$)	CHF_{ver} ($\text{kW}\cdot\text{m}^{-2}$)	$CHFR$	I
367.	0.814	0.47623	0.00560	1744.	444.	3.93206	2
367.	0.658	0.47623	0.00560	1396.	1139.	1.22573	2
367.	0.636	0.47623	0.00560	1337.	1329.	1.00646	2
367.	0.673	0.47623	0.00560	1396.	1008.	1.38511	2
794.	0.224	0.45596	0.00560	3489.	2313.	1.50871	2
781.	0.377	0.45596	0.00560	4070.	1596.	2.55041	2
768.	0.475	0.45596	0.00560	4361.	1114.	3.91529	2
755.	0.516	0.45596	0.00560	4303.	965.	4.46131	2
745.	0.538	0.45596	0.00560	4187.	940.	4.45238	2
735.	0.446	0.45596	0.00560	3024.	1360.	2.22268	2
596.	0.303	0.45596	0.00560	3082.	2419.	1.27415	2
582.	0.456	0.45596	0.00560	3373.	1923.	1.75384	2
573.	0.556	0.45596	0.00560	3663.	1395.	2.62641	2
561.	0.622	0.45596	0.00560	3663.	1029.	3.56097	2
554.	0.563	0.45596	0.00560	3140.	1403.	2.23772	2
551.	0.478	0.45596	0.00560	2384.	1937.	1.23076	2
397.	0.269	0.45596	0.00560	1919.	2688.	0.71388	2
390.	0.603	0.45596	0.00560	2907.	1530.	1.90003	2
381.	0.707	0.45596	0.00560	2966.	697.	4.25384	2
374.	0.777	0.45596	0.00560	3024.	496.	6.09044	2
369.	0.723	0.45596	0.00560	2675.	669.	3.99542	2
367.	0.568	0.45596	0.00560	1919.	1835.	1.04591	2
$L_h/D = 161.0$							
797.	0.518	0.70927	0.00620	2035.	1317.	1.54487	2
767.	0.641	0.70927	0.00620	1919.	634.	3.02864	2
729.	0.702	0.70927	0.00620	1686.	515.	3.27405	2
597.	0.632	0.70927	0.00620	1744.	1025.	1.70131	2
576.	0.712	0.70927	0.00620	1570.	625.	2.51181	2
547.	0.744	0.70927	0.00620	1337.	570.	2.34748	2

Table A-1 (Continue)
Fluid: Water
Source: Ishigai et al. (1970a)

$L_h/D = 161.0$							
G ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	X_{cr}	P (MPa)	D (m)	CHF_{hor} ($\text{kW}\cdot\text{m}^{-2}$)	CHF_{ver} ($\text{kW}\cdot\text{m}^{-2}$)	CHFR	I
398.	0.723	0.70927	0.00620	1279.	871.	1.46859	2
384.	0.902	0.70927	0.00620	1279.	495.	2.58545	2
365.	0.727	0.70927	0.00620	872.	927.	0.94048	2
$L_h/D = 121.0$							
797.	0.524	0.70927	0.00620	2733.	1275.	2.14326	2
767.	0.606	0.70927	0.00620	2442.	724.	3.37353	2
729.	0.671	0.70927	0.00620	2152.	603.	3.57040	2
597.	0.655	0.70927	0.00620	2384.	893.	2.66994	2
576.	0.712	0.70927	0.00620	2098.	625.	3.34908	2
547.	0.653	0.70927	0.00620	1570.	1002.	1.56669	2
398.	0.780	0.70927	0.00620	1803.	641.	2.81200	2
384.	0.854	0.70927	0.00620	1628.	539.	3.02109	2
365.	0.802	0.70927	0.00620	1279.	605.	2.11316	2
$L_h/D = 65.4$							
135.	0.643	0.11652	0.01530	768.	735.	1.04383	2
134.	0.445	0.11652	0.01530	488.	830.	0.58815	2
134.	0.591	0.11652	0.01530	605.	795.	0.76093	2
134.	0.657	0.11652	0.01530	640.	715.	0.89443	2
127.	0.613	0.11652	0.01530	721.	763.	0.94489	2
125.	0.597	0.11652	0.01530	663.	780.	0.85028	2
124.	0.467	0.11652	0.01530	477.	809.	0.58921	2
124.	0.504	0.11652	0.01530	500.	801.	0.62432	2
124.	0.649	0.11652	0.01530	628.	711.	0.88274	2
124.	0.667	0.11652	0.01530	605.	687.	0.88051	2
96.	0.682	0.11652	0.01530	570.	617.	0.92396	2
96.	0.582	0.11652	0.01530	465.	737.	0.63146	2
96.	0.517	0.11652	0.01530	395.	755.	0.52397	2
96.	0.561	0.11652	0.01530	407.	742.	0.54824	2
96.	0.660	0.11652	0.01530	488.	646.	0.75626	2

Table A-1 (Continue)
Fluid: Water
Source: Ishigai et al. (1970a)

$L_h/D = 65.4$							
G ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	X_{cr}	P (MPa)	D (m)	CHF_{hor} ($\text{kW}\cdot\text{m}^{-2}$)	CHF_{ver} ($\text{kW}\cdot\text{m}^{-2}$)	$CHFR$	I
96.	0.766	0.11652	0.01530	547.	470.	1.16406	2
96.	0.714	0.11652	0.01530	500.	563.	0.88802	2

Table A-1 (Continue)
 Fluid: Freon-12
 Source: Merilo and Ahmad (1979)

$L_h/D = 194.0$							
G ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	X_{cr}	P (MPa)	D (m)	CHF_{hor} ($\text{kW}\cdot\text{m}^{-2}$)	CHF_{ver} ($\text{kW}\cdot\text{m}^{-2}$)	$CHFR$	I
1600.	0.3150	1.0500	0.00530	90.	167.	0.53860	2
1600.	0.3000	1.0500	0.00530	97.	176.	0.55232	2
1600.	0.2800	1.0500	0.00530	105.	190.	0.55134	2
1600.	0.2700	1.0500	0.00530	113.	198.	0.57112	2
2700.	0.2300	1.0500	0.00530	150.	180.	0.83202	2
2700.	0.2150	1.0500	0.00530	166.	188.	0.88114	2
2700.	0.2250	1.0500	0.00530	170.	183.	0.92903	2
4100.	0.1800	1.0500	0.00530	163.	176.	0.92543	2
4100.	0.1500	1.0500	0.00530	176.	179.	0.98056	2
4100.	0.1300	1.0500	0.00530	190.	186.	1.02109	2
4100.	0.1150	1.0500	0.00530	206.	191.	1.07845	2
5400.	0.1600	1.0500	0.00530	159.	187.	0.85064	2
5400.	0.1050	1.0500	0.00530	186.	210.	0.88546	2
5400.	0.0750	1.0500	0.00530	212.	239.	0.88729	2
5400.	0.0600	1.0500	0.00530	257.	255.	1.00874	2
6800.	0.0750	1.0500	0.00530	211.	252.	0.83687	2
6800.	0.0600	1.0500	0.00530	243.	265.	0.91633	2
1600.	0.2700	1.5200	0.00530	85.	112.	0.75905	2
1600.	0.2600	1.5200	0.00530	106.	117.	0.90853	2
1600.	0.2150	1.5200	0.00530	128.	134.	0.95223	2
2700.	0.2200	1.5200	0.00530	120.	115.	1.04492	2
2700.	0.1750	1.5200	0.00530	176.	131.	1.34570	2
2700.	0.1600	1.5200	0.00530	192.	137.	1.39969	2
4100.	0.1650	1.5200	0.00530	142.	132.	1.07578	2
4100.	0.1100	1.5200	0.00530	176.	158.	1.11461	2
4100.	0.0900	1.5200	0.00530	220.	177.	1.24285	2
4100.	0.0600	1.5200	0.00530	266.	217.	1.22608	2
6800.	0.1950	1.5200	0.00530	165.	204.	0.81063	2
6800.	0.1100	1.5200	0.00530	185.	232.	0.79615	2

Table A-1 (Continue)
Fluid: Freon-12
Source: Merilo and Ahmad (1979)

$L_h/D = 194.0$							
G ($\text{kg.m}^{-2}.\text{s}^{-1}$)	X_{cr}	P (MPa)	D (m)	CHF_{hor} (kW.m^{-2})	CHF_{ver} (kW.m^{-2})	$CHFR$	I
6800.	0.0750	1.5200	0.00530	255.	266.	0.95751	2
6800.	0.0460	1.5200	0.00530	325.	302.	1.07766	2
8100.	0.1100	1.5200	0.00530	215.	268.	0.80158	2
8100.	0.0740	1.5200	0.00530	264.	301.	0.87788	2
8100.	0.0750	1.5200	0.00530	294.	300.	0.98099	2
8100.	0.0600	1.5200	0.00530	353.	315.	1.12039	2
$L_h/D = 290.0$							
1360.	0.3333	1.0500	0.01260	40.	133.	0.30067	2
1360.	0.3900	1.0500	0.01260	38.	109.	0.34911	2
1360.	0.4500	1.0500	0.01260	38.	87.	0.43641	2
1360.	0.4700	1.0500	0.01260	36.	80.	0.44960	2
2720.	0.2400	1.0500	0.01260	68.	130.	0.52151	2
2720.	0.2900	1.0500	0.01260	61.	104.	0.58710	2
1600.	0.3850	1.0500	0.00530	71.	127.	0.55764	2
1600.	0.3600	1.0500	0.00530	75.	142.	0.52993	2
1600.	0.3500	1.0500	0.00530	80.	147.	0.54344	2
1600.	0.3650	1.0500	0.00530	85.	139.	0.61289	2
4100.	0.2600	1.0500	0.00530	126.	143.	0.88191	2
4100.	0.2400	1.0500	0.00530	138.	155.	0.89260	2
4100.	0.2000	1.0500	0.00530	152.	174.	0.87408	2
4100.	0.1950	1.0500	0.00530	156.	174.	0.89420	2
5400.	0.1900	1.0500	0.00530	152.	184.	0.82573	2
5400.	0.1600	1.0500	0.00530	157.	187.	0.83994	2
5400.	0.1400	1.0500	0.00530	166.	193.	0.86102	2
5400.	0.1100	1.0500	0.00530	180.	208.	0.86708	2
6800.	0.1850	1.0500	0.00530	159.	194.	0.81865	2
6800.	0.1500	1.0500	0.00530	163.	197.	0.82791	2
6800.	0.1300	1.0500	0.00530	170.	210.	0.80846	2
6800.	0.1000	1.0500	0.00530	190.	230.	0.82476	2

Table A-1 (Continue)
Fluid: Freon-12
Source: Merilo and Ahmad (1979)

G (kg.m ⁻² .s ⁻¹)	X _{cr}	P (MPa)	L _h /D = 290.0				I
			D (m)	CHF _{hor} (kW.m ⁻²)	CHF _{vcr} (kW.m ⁻²)	CHFR	
6800.	0.0800	1.0500	0.00530	209.	248.	0.84349	2
8100.	0.1700	1.0500	0.00530	173.	204.	0.84770	2
8100.	0.1300	1.0500	0.00530	181.	222.	0.81558	2
8100.	0.1100	1.0500	0.00530	192.	239.	0.80468	2
8100.	0.0800	1.0500	0.00530	213.	261.	0.81641	2
1600.	0.3600	1.5200	0.00530	67.	72.	0.93488	2
1600.	0.3250	1.5200	0.00530	77.	87.	0.88530	2
1600.	0.2900	1.5200	0.00530	80.	103.	0.77971	2
1600.	0.2800	1.5200	0.00530	90.	107.	0.83883	2
2700.	0.2500	1.5200	0.00530	87.	107.	0.81393	2
2700.	0.2350	1.5200	0.00530	117.	111.	1.05534	2
2700.	0.2150	1.5200	0.00530	130.	116.	1.11908	2
2700.	0.2100	1.5200	0.00530	139.	117.	1.18306	2
2700.	0.1900	1.5200	0.00530	152.	124.	1.22186	2
4100.	0.2650	1.5200	0.00530	95.	112.	0.84552	2
4100.	0.1600	1.5200	0.00530	145.	133.	1.09102	2
4100.	0.1300	1.5200	0.00530	163.	146.	1.11407	2
4100.	0.1100	1.5200	0.00530	187.	158.	1.18427	2
5400.	0.2750	1.5200	0.00530	130.	154.	0.84182	2
5400.	0.2800	1.5200	0.00530	133.	154.	0.86331	2
5400.	0.1900	1.5200	0.00530	137.	164.	0.83340	2
5400.	0.1150	1.5200	0.00530	158.	191.	0.82788	2
5400.	0.1250	1.5200	0.00530	162.	185.	0.87553	2
5400.	0.0950	1.5200	0.00530	194.	206.	0.94297	2
5400.	0.0930	1.5200	0.00530	217.	208.	1.04229	2
5400.	0.0900	1.5200	0.00530	242.	212.	1.14210	2
5400.	0.0650	1.5200	0.00530	267.	243.	1.10021	2
5400.	0.0100	1.5200	0.00530	311.	337.	0.92409	2
6800.	0.2600	1.5200	0.00530	150.	202.	0.74373	2

Table A-1 (Continue)

Fluid: Freon-12

Source: Merilo and Ahmad (1979)

$L_h/D = 290.0$							
G ($\text{kg.m}^{-2}.\text{s}^{-1}$)	X_{cr}	P (MPa)	D (m)	CHF_{hor} (kW.m^{-2})	CHF_{ver} (kW.m^{-2})	$CHFR$	I
6800.	0.1980	1.5200	0.00530	162.	203.	0.79732	2
6800.	0.1750	1.5200	0.00530	165.	206.	0.80108	2
6800.	0.0830	1.5200	0.00530	241.	257.	0.93657	2
6800.	0.0650	1.5200	0.00530	300.	278.	1.08085	2
8100.	0.2650	1.5200	0.00530	176.	244.	0.72107	2
8100.	0.2640	1.5200	0.00530	181.	244.	0.74128	2
8100.	0.1660	1.5200	0.00530	189.	243.	0.77683	2
8100.	0.0980	1.5200	0.00530	220.	276.	0.79672	2
8100.	0.0770	1.5200	0.00530	280.	298.	0.94070	2
$L_h/D = 389.0$							
1600.	0.4400	1.0500	0.00530	61.	100.	0.60707	2
1600.	0.4400	1.0500	0.00530	64.	100.	0.63693	2
1600.	0.4000	1.0500	0.00530	66.	119.	0.55556	2
1600.	0.3800	1.0500	0.00530	70.	130.	0.53778	2
4100.	0.2800	1.0500	0.00530	115.	129.	0.89111	2
4100.	0.2600	1.0500	0.00530	124.	143.	0.86791	2
4100.	0.2500	1.0500	0.00530	131.	150.	0.87460	2
4100.	0.2250	1.0500	0.00530	136.	162.	0.84034	2
5400.	0.2800	1.0500	0.00530	132.	153.	0.86296	2
5400.	0.2600	1.0500	0.00530	140.	157.	0.88944	2
5400.	0.2200	1.0500	0.00530	145.	174.	0.83463	2
5400.	0.1900	1.0500	0.00530	151.	184.	0.82029	2
5400.	0.1600	1.0500	0.00530	158.	187.	0.84529	2
5400.	0.1250	1.0500	0.00530	172.	200.	0.85917	2
6800.	0.2600	1.0500	0.00530	155.	173.	0.89570	2
6800.	0.2200	1.0500	0.00530	156.	184.	0.84811	2
6800.	0.1850	1.0500	0.00530	160.	194.	0.82380	2
6800.	0.1400	1.0500	0.00530	164.	204.	0.80559	2
6800.	0.1150	1.0500	0.00530	172.	220.	0.78067	2

Table A-1 (Continue)
Fluid: Freon-12
Source: Merilo and Ahmad (1979)

G (kg.m ⁻² .s ⁻¹)	X _{cr}	P (MPa)	L _h /D = 389.0				I
			D (m)	CHF _{hor} (kW.m ⁻²)	CHF _{ver} (kW.m ⁻²)	CHFR	
8100.	0.2400	1.0500	0.00530	171.	185.	0.92677	2
8100.	0.1900	1.0500	0.00530	172.	203.	0.84768	2
8100.	0.1400	1.0500	0.00530	174.	214.	0.81464	2
8100.	0.1200	1.0500	0.00530	183.	230.	0.79473	2
8100.	0.1050	1.0500	0.00530	193.	243.	0.79498	2
8100.	0.0700	1.0500	0.00530	242.	268.	0.90340	2
1600.	0.4200	1.5200	0.00530	58.	50.	1.16873	2
1600.	0.3800	1.5200	0.00530	65.	63.	1.03308	2
1600.	0.3500	1.5200	0.00530	73.	76.	0.96001	2
1600.	0.3400	1.5200	0.00530	76.	80.	0.94509	2
2700.	0.2750	1.5200	0.00530	67.	96.	0.69756	2
2700.	0.2400	1.5200	0.00530	82.	110.	0.74859	2
4100.	0.3000	1.5200	0.00530	73.	110.	0.66331	2
4100.	0.2500	1.5200	0.00530	101.	113.	0.89109	2
4100.	0.2450	1.5200	0.00530	105.	115.	0.91643	2
4100.	0.2150	1.5200	0.00530	124.	122.	1.01674	2
4100.	0.1700	1.5200	0.00530	136.	131.	1.03745	2
4100.	0.1450	1.5200	0.00530	154.	138.	1.11906	2
5400.	0.3150	1.5200	0.00530	111.	148.	0.75018	2
5400.	0.2400	1.5200	0.00530	125.	158.	0.79318	2
5400.	0.1950	1.5200	0.00530	135.	164.	0.82506	2
5400.	0.1700	1.5200	0.00530	140.	167.	0.83613	2
5400.	0.1200	1.5200	0.00530	157.	188.	0.83538	2
5400.	0.1050	1.5200	0.00530	175.	197.	0.88984	2
6800.	0.3050	1.5200	0.00530	136.	198.	0.68784	2
6800.	0.2820	1.5200	0.00530	142.	200.	0.71048	2
6800.	0.2800	1.5200	0.00530	150.	200.	0.74989	2
6800.	0.2400	1.5200	0.00530	160.	203.	0.78974	2
6800.	0.2000	1.5200	0.00530	163.	203.	0.80321	2

Table A-1 (Continue)
Fluid: Freon-12
Source: Merilo and Ahmad (1979)

G (kg.m ⁻² .s ⁻¹)	X _{cr}	P (MPa)	L _h /D = 389.0				I
			D (m)	CHF _{hor} (kW.m ⁻²)	CHF _{ver} (kW.m ⁻²)	CHFR	
6800.	0.1500	1.5200	0.00530	169.	209.	0.80858	2
6800.	0.0950	1.5200	0.00530	235.	244.	0.96379	2
8100.	0.3050	1.5200	0.00530	167.	241.	0.69276	2
8100.	0.2300	1.5200	0.00530	176.	243.	0.72331	2
8100.	0.1400	1.5200	0.00530	191.	251.	0.76205	2
8100.	0.1000	1.5200	0.00530	228.	274.	0.83187	2
8100.	0.0850	1.5200	0.00530	273.	289.	0.94316	2
L _h /D = 575.0							
1600.	0.4650	1.0500	0.00530	43.	89.	0.48296	2
1600.	0.4950	1.0500	0.00530	48.	75.	0.63748	2
1600.	0.4800	1.0500	0.00530	50.	82.	0.60853	2
1600.	0.4650	1.0500	0.00530	55.	89.	0.61774	2
4100.	0.3600	1.0500	0.00530	83.	90.	0.92270	2
4100.	0.3500	1.0500	0.00530	92.	94.	0.97699	2
4100.	0.3300	1.0500	0.00530	99.	103.	0.96497	2
4100.	0.3150	1.0500	0.00530	105.	109.	0.96407	2
4100.	0.3050	1.0500	0.00530	108.	113.	0.95468	2
4100.	0.3050	1.0500	0.00530	110.	113.	0.97236	2
5400.	0.3400	1.0500	0.00530	111.	138.	0.80241	2
5400.	0.3250	1.0500	0.00530	118.	142.	0.83009	2
5400.	0.3050	1.0500	0.00530	123.	147.	0.83533	2
5400.	0.2950	1.0500	0.00530	132.	150.	0.88217	2
5400.	0.2700	1.0500	0.00530	138.	155.	0.88928	2
6800.	0.3400	1.0500	0.00530	134.	181.	0.73886	2
6800.	0.3150	1.0500	0.00530	144.	183.	0.78585	2
6800.	0.2950	1.0500	0.00530	151.	183.	0.82535	2
6800.	0.2950	1.0500	0.00530	154.	183.	0.84174	2
6800.	0.2400	1.0500	0.00530	159.	175.	0.90965	2
8100.	0.3200	1.0500	0.00530	170.	219.	0.77454	2

Table A-1 (Continue)
 Fluid: Freon-12
 Source: Merilo and Ahmad (1979)

$L_h/D = 575.0$							
G ($\text{kg.m}^{-2}.\text{s}^{-1}$)	X_{cr}	P (MPa)	D (m)	CHF_{hor} (kW.m^{-2})	CHF_{ver} (kW.m^{-2})	$CHFR$	I
8100.	0.2800	1.0500	0.00530	171.	203.	0.84396	2
8100.	0.2200	1.0500	0.00530	171.	193.	0.88410	2
8100.	0.2100	1.0500	0.00530	172.	198.	0.86927	2
1600.	0.4650	1.5200	0.00530	48.	39.	1.21819	2
1600.	0.4350	1.5200	0.00530	50.	46.	1.08182	2
1600.	0.4000	1.5200	0.00530	55.	54.	1.01532	2
1600.	0.3900	1.5200	0.00530	58.	59.	0.99070	2
2700.	0.3050	1.5200	0.00530	52.	83.	0.62686	2
2700.	0.2650	1.5200	0.00530	60.	100.	0.59770	2
2700.	0.2400	1.5200	0.00530	70.	110.	0.63904	2
2700.	0.2350	1.5200	0.00530	74.	111.	0.66748	2
4100.	0.3400	1.5200	0.00530	62.	91.	0.67995	2
4100.	0.3100	1.5200	0.00530	73.	105.	0.69302	2
4100.	0.2700	1.5200	0.00530	90.	112.	0.80337	2
4100.	0.2450	1.5200	0.00530	104.	115.	0.90771	2
4100.	0.2350	1.5200	0.00530	110.	117.	0.93988	2
5400.	0.3800	1.5200	0.00530	88.	128.	0.68764	2
5400.	0.3200	1.5200	0.00530	105.	146.	0.71708	2
5400.	0.2800	1.5200	0.00530	122.	154.	0.79191	2
5400.	0.2200	1.5200	0.00530	134.	160.	0.83631	2
6800.	0.3950	1.5200	0.00530	119.	186.	0.63994	2
6800.	0.3100	1.5200	0.00530	131.	197.	0.66475	2
6800.	0.2700	1.5200	0.00530	149.	201.	0.74182	2
6800.	0.1700	1.5200	0.00530	165.	207.	0.79872	2
6800.	0.1450	1.5200	0.00530	175.	212.	0.82575	2

Table A-1 (Continue)
Fluid: Freon-12
Source: Merilo and Ahmad (1979)

$L_h/D = 575.0$							
G ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	X_{cr}	P (MPa)	D (m)	CHF_{hor} ($\text{kW}\cdot\text{m}^{-2}$)	CHF_{ver} ($\text{kW}\cdot\text{m}^{-2}$)	$CHFR$	I
8100.	0.3200	1.5200	0.00530	159.	242.	0.65820	2
8100.	0.2850	1.5200	0.00530	166.	242.	0.68521	2
8100.	0.2700	1.5200	0.00530	172.	244.	0.70600	2
8100.	0.2250	1.5200	0.00530	180.	243.	0.74136	2
8100.	0.1800	1.5200	0.00530	182.	242.	0.75206	2
8100.	0.1460	1.5200	0.00530	191.	247.	0.77289	2
8100.	0.1300	1.5200	0.00530	203.	256.	0.79142	2

Appendix B

FLUID PROPERTIES EVALUATION

B.1 Water Properties Evaluation

The property code (UOCODE) developed by Cheng et al. (1987) was used for the evaluation of water properties. It is a convenient code to use because only pressure and temperature are required as the input parameters. The output provided by the UOCODE are the specific volume, density, enthalpy, specific heat, thermal conductivity, viscosity, surface tension and latent heat of vaporization at the given pressure.

Range of validity for the UOCODE covers a wide range of thermodynamic states from the triple point to beyond critical point of water, i.e.

$$\begin{aligned}0.01^{\circ}\text{C} < T < 800^{\circ}\text{C} \\ 0.6113\text{kPa} < P < 22.09\text{MPa}\end{aligned}$$

Comparison with data from steam table (1967 ASME steam table) were made for various properties at both saturated and superheated regions. The results are shown in figures B1 to B5. The predictions agree very well with the experimental data for most of the region except at conditions near the critical point. Undoubtedly, this property code is accurate and can be used for thermalhydraulic analysis with good confidence.

B.2 Non-aqueous Fluid properties Evaluation

A software for non-aqueous fluid properties evaluation was developed based on a four parameter equation of state. Thermodynamic properties of the fluids were obtained through the derivatives of the equation of state while the transport properties were evaluated through the use of other empirical correlations. Adachi et al.'s equation of state (1983) is chosen because it has a simple cubic form.

$$P = \frac{RT}{V - b_1} - \frac{a(T)}{(V - b_2)(V + b_3)} \quad (\text{B.1})$$

It has one temperature-dependent parameter $a(T)$ and three temperature independent parameters b_1 , b_2 and b_3 . The parameters can be expressed as follows:

$$a(T) = \frac{AR^2T_c^2}{P_c} [1 + \alpha(1 - T_r^{1/2})]^2 \quad (\text{B.2})$$

$$A = 0.44869 + 0.0402\omega + 0.01111\omega^2 - 0.00576\omega^3 \quad (\text{B.3})$$

$$\alpha = 0.4070 + 1.3787\omega - 0.2933\omega^2 \quad (\text{B.4})$$

and

$$b_i = \frac{B_i RT_c}{P_c} \quad i = 1, 2, 3 \quad (\text{B.5})$$

where

$$B_1 = 0.08974 - 0.03452\omega + 0.00330\omega^2 \quad (\text{B.6})$$

$$B_2 = 0.03686 + 0.00405\omega - 0.01073\omega^2 + 0.00157\omega^3 \quad (\text{B.7})$$

$$B_3 = 0.15400 + 0.14122\omega - 0.00272\omega^2 - 0.00484\omega^3 \quad (\text{B.8})$$

R is the universal gas constant, ω is the acentric factor of the substance and T_r is the reduced temperature. The applicability of the proposed equation of state was tested by the authors in terms of its calculated values of several pure-component properties such as the compressibility factor (Z), fugacity coefficient in the form of $\log(f/P)$ and isothermal enthalpy departure function $(H^0 - H)_T/RT_c$. The calculated values were compared with the values reported in Pitzer's tables (1955) along with

four other widely used equations of state. A summary of comparison is reported in Table B-1. The comparison was made at twenty-two T_r and twenty P_r conditions ($0.8 < T_r < 4.0$, $0.2 < P_r < 8.0$), using six values of acentric factor (0.0 to 0.5 at 0.1 intervals). The average absolute deviations obtained for these three properties from Adachi et al.'s equation are the lowest.

Equation (B-1) is also valid for saturation state. Adachi et al. (1983) have compared the experimental data with the calculated values of three saturated properties (vapour pressure, liquid and vapour volumes) obtained from equation (B-1) and those obtained from the other selected equations of state. Experimental values of eighteen pure components were used in the comparison and the results are summarized in Table B-2. The overall average absolute deviation is the lowest for equation (B-1) and thus indicates that it yields satisfactory values in the overall evaluation.

Estimation of Saturation Pressure

At saturation, the fugacity coefficient of liquid must be equal to that of vapour in order to have thermodynamic equilibrium. Adachi et al. derived an expression for fugacity coefficient based on their equation of state:

$$\ln(f/P) = Z - 1 - \ln Z + \ln \frac{Z}{Z - B_1 P_r / T_r} + \frac{A(T_r)}{T_r(B_2 + B_3)} \ln \frac{Z - B_2 P_r / T_r}{Z + B_3 P_r / T_r} \quad (\text{B.9})$$

For a given temperature, an iteration process is required in order to determine the saturation pressure; i.e., in order to have thermodynamic equilibrium, the condition that $\ln(f/P)_V = \ln(f/P)_L$ must be satisfied. To avoid this time consuming iteration process, Lee-Kesler's (1975) equation for vapour pressure is used. Their equation only required the critical pressure, critical temperature and the acentric factor of the substance. It is derived from the Pitzer table and has the following form:

$$\ln P_r^{\text{sat}} = f^{(0)}(T_r) + \omega f^{(1)}(T_r) \quad (\text{B.10})$$

where

$$f^{(0)}(T_r) = 5.92714 - 6.09648T_r^{-1} - 1.28862 \ln T_r + 0.16934T_r^6 \quad (B.11)$$

$$f^{(0)}(T_r)^* = 15.2518 - 15.6875T_r^{-1} - 13.4721 \ln T_r + 0.43577T_r^6 \quad (B.12)$$

Equations (B.10) to (B.12) were used to estimate the saturation pressure with good accuracy.

Derivation of Volume from Equation of State

The volume is not expressed explicitly in equation (B.1). With given temperature and pressure, an iteration process is necessary for the determination of molar volume. The Newton-Raphson method was used because the method converges rapidly. For the superheated region, only one root would be expected (figure B6). The ideal gas volume is chosen for the initial guess for this case because it is close to the actual value and thus allows earlier convergence. For the saturation region, there are three possible roots because the equation of state is in cubic form. Figure B7 shows a typical P - V - T relation at saturation. The lowest root is taken as the solution for the saturated liquid volume while the highest root corresponds to the saturated vapour volume. To obtain the lowest root, the initial guess has to be very small such as having a value of 0.001.

Derivation of Equation for Specific Enthalpy

The variation of enthalpy between two states is independent of the path chosen to pass from one state to the other. There are an infinite number of possible calculation paths, all of which give the same numerical result (see figure 15). The enthalpy difference between two states can be expressed as

$$H = (H_P - H^0)_T - (H_{P_{ref}} - H^0)_{T_{ref}} + \int_{T_{ref}}^T C_P^0 dT \quad (B.13)$$

From the equation of state, the departure function was derived by Adachi et al. as

$$\frac{(H - H^0)_T}{RT_c} = (Z - 1)T_r + \frac{1}{(B_2 + B_3)} \left[A(T_r) - T_r \frac{dA(T_r)}{dT_r} \right] \ln \frac{Z - B_2 P_r / T_r}{Z + B_3 P_r / T_r}$$

or

$$(H - H^0)_T = RT(Z - 1) + \frac{1}{(b_2 + b_3)} \left[a(T) - T \frac{da(T)}{dT} \right] \ln \frac{V - b_2}{V + b_3} \quad (\text{B.14})$$

where

$$A(T_r) = A[1 + \alpha(1 - T_r^{1/2})]^2 \quad (\text{B.15})$$

The ideal gas specific heat at zero pressure for most substances can be expressed in terms of a third order polynomial function of temperature

$$C_P^0 = A + BT + CT^2 + DT^3 \quad (\text{B.16})$$

The constants A , B , C and D are obtained experimentally and a list of substances with these constants is provided by Reid et al. (1977) and other engineering handbooks.

Derivation of Equation for Specific Heat Capacity

Specific heat capacity at constant pressure is defined as the rate of change of enthalpy with temperature at constant pressure, i.e.;

$$C_P - C_P^0 = \frac{\partial}{\partial T}(H - H^0) |_P \quad (\text{B.17})$$

Taking the partial derivative of equation (B.14) w.r.t temperature at constant pressure yields

$$\begin{aligned} C_P - C_P^0 &= P \frac{\partial V}{\partial T} |_P - R + \frac{1}{(b_2 + b_3)} \left\{ -T \frac{d^2 a(T)}{dT^2} \ln \frac{V - b_2}{V + b_3} \right. \\ &\quad \left. + \frac{\partial V}{\partial T} |_P \left(\frac{b_2 + b_3}{(V - b_2)(V + b_3)} \right) \left[a(T) - T \frac{da(T)}{dT} \right] \right\} \\ &= -\frac{1}{(b_2 + b_3)} T \frac{d^2 a(T)}{dT^2} \ln \frac{V - b_2}{V + b_3} - R \\ &\quad + \frac{\partial V}{\partial T} |_P \left[P + \frac{a(T)}{(V - b_2)(V + b_3)} - T \frac{da(T)}{dT} \frac{1}{(V - b_2)(V + b_3)} \right] \\ &= -\frac{1}{(b_2 + b_3)} T \frac{d^2 a(T)}{dT^2} \ln \frac{V - b_2}{V + b_3} - R \\ &\quad + \frac{\partial V}{\partial T} |_P \left[\frac{RT}{V - b_1} - T \frac{da(T)}{dT} \frac{1}{(V - b_2)(V + b_3)} \right] \end{aligned} \quad (\text{B.18})$$

where

$$\frac{\partial V}{\partial T} |_P = -\frac{(\partial P / \partial T)_V}{(\partial P / \partial V)_T} \quad (\text{Maxwell's Law}) \quad (\text{B.19})$$

and $da(T)/dT$ and $d^2a(T)/dT^2$ can be obtained by taking the derivatives of equation (B.2) w.r.t T once and twice respectively, i.e.

$$\frac{da(T)}{dT} = -\frac{a\alpha}{T_c} \left[\frac{1+\alpha}{T_r^{1/2}} - \alpha \right] \quad (\text{B.20})$$

$$\frac{d^2a(T)}{dT^2} = \frac{a\alpha(1+\alpha)}{2T_c^2} T_r^{-3/2} \quad (\text{B.21})$$

$(\partial P/\partial T)_V$ and $(\partial P/\partial V)_T$ can be derived from the equation of state directly. After taking the partial derivatives of equation (B.1) and simplifying, the final equations for $(\partial P/\partial T)_V$ and $(\partial P/\partial V)_T$ are

$$\frac{\partial P}{\partial T} \Big|_V = \frac{R}{V-b_1} - \frac{da(T)}{dT} \frac{1}{(V-b_2)(V+b_3)} \quad (\text{B.22})$$

$$\frac{\partial P}{\partial V} \Big|_T = -\frac{RT}{(V-b_1)^2} + \frac{a(T)}{(b_2+b_3)} \left[\frac{1}{(V-b_2)^2} - \frac{1}{(V+b_3)^2} \right] \quad (\text{B.23})$$

With any P - V - T state, the specific heat capacity is calculated from equations (B.18) to (B.23).

Evaluation of Transport Properties for Non-aqueous Fluids

All the present prediction methods for transport properties are either semi-empirical or purely empirical in nature. There is no generalized and accurate analytical prediction method for viscosity, thermal conductivity and surface tension. The equations used for transport properties prediction are discussed in a fair amount of detail in Chapter 4. This section summarizes the equations used for transport properties evaluations and their sources.

Low-Pressure Gas Viscosity

The most common form of correlation for the prediction of viscosity at low pressure is the one which makes use of corresponding states principle. This type of correlation is easy to use and only requires the knowledge of the critical properties and molecular weight of the substance. These constants are readily available in the open literature. Equation suggested by Thodos et al. (1970) was chosen for the present work:

$$\mu^0 \xi = 4.610 T_r^{0.618} - 2.04 e^{-0.449 T_r} + 1.94 e^{-4.058 T_r} + 0.1 \quad (\text{B.24})$$

where

$$\xi = T_c^{1/6} M^{-1/2} P_c^{-2/3}$$

T_c = Critical temperature, K

P_c = Critical pressure, atm

M = Molecular weight

μ^0 = Low-pressure gas viscosity, micro-poise

The expected error for this equation is normally between 1 and 3 percent for non-polar gases. It should not be used for hydrogen, helium, diatomic halogen gases and polar gases.

Dense-Gas Viscosity

Jossi et al. (1962) have developed a correlation relating the dense-gas viscosity to the low density viscosity. Their equation is recommended by Reid et al. (1977) as the most accurate prediction method for non-polar dense gas viscosity. They have related the dense-gas viscosity to the low density gas viscosity in terms of the reduced density:

$$[(\mu - \mu^0)\xi + 1]^{0.25} = 1.0230 + 0.23364\rho_r + 0.58533\rho_r^2 - 0.40758\rho_r^3 + 0.093324\rho_r^4 \quad (\text{B.25})$$

where

ρ_r = reduced density

μ = dense-gas viscosity, micro-poise

Equation (B.25) is valid for $0.1 < \rho_r < 3.0$. It can also be used for the estimation of saturated liquid viscosity as long the reduced density is within the specified limits.

Liquid Viscosity

For $T_r < 0.75$, the relation of Van Velzen et al. (1972) is used for the estimation of saturated liquid viscosity. They assumed that $\log \mu_L$ is linear in $1/T$, i.e.

$$\log \mu_L = B \left(\frac{1}{T} - \frac{1}{T^0} \right) \quad (B.26)$$

where

μ_L = Liquid viscosity, cP

T = Temperature, K

and B and T^0 are correlation constants for each specific substance. A list of these constants for different substances was tabulated by Reid et al. (1977).

For saturated liquids at higher temperature, corresponding-states relation is used. The correlation suggested by Letsou and Stiel (1973) is easy to use and yields accurate results up to $T_r = 0.92$. Their correlation is shown below.

$$\mu_L \xi = (\mu_L \xi)^{(0)} + \omega (\mu_L \xi)^{(1)} \quad (B.27)$$

where

$$(\mu_L \xi)^{(0)} = 0.015174 - 0.02135T_r + 0.0075T_r^2 \quad (B.28)$$

$$(\mu_L \xi)^{(1)} = 0.042552 - 0.07674T_r + 0.0340T_r^2 \quad (B.29)$$

The viscosity evaluated (μ_L) is in centipoise and ξ is defined in equation (B.24).

Low Density Gas Thermal Conductivity

A simple and accurate method for the prediction of thermal conductivity for low density gases is the well-known Eucken correlation for polyatomic gases.

$$\frac{\lambda^0 M}{\mu^0} = C_v^0 + 4.47 \quad (B.30)$$

λ^0 is the low density gas thermal conductivity in cal/g-mole.K , μ^0 is the corresponding low density gas viscosity in poise, M is the molecular weight and C_v^0 is the ideal gas specific heat at constant volume and can be obtained from

$$C_v^0 = C_p^0 - R \quad (B.31)$$

which has the unit of *cal/g-mole.K*.

Dense Gas Thermal Conductivity

At higher pressure (or density), simple kinetic theory would not be sufficient to account for the interactive forces between the molecules. Additional parameter such as the density of the gas has to be taken into account. Stiel and Thodos (1964) suggested the following correlation for the dense gas thermal conductivity estimation.

$$\begin{aligned}(\lambda - \lambda^0)\Gamma Z_c^5 &= 14.0 \times 10^{-8}(e^{0.535\rho_r} - 1) & \rho_r < 0.5 \\(\lambda - \lambda^0)\Gamma Z_c^5 &= 13.1 \times 10^{-8}(e^{0.67\rho_r} - 1.069) & 0.5 < \rho_r < 2.0 \\(\lambda - \lambda^0)\Gamma Z_c^5 &= 2.976 \times 10^{-8}(e^{1.155\rho_r} - 2.016) & 2.0 < \rho_r < 2.8\end{aligned}\quad (\text{B.32})$$

where $\Gamma = T_c^{1/6} M^{1/2} P_c^{-2/3}$ and Z_c is the critical compressibility factor of the substance. T_c is in Kelvin, P_c is in atm. and M is in *gm/g-mole*. Again, this relation is only good for non-polar substances.

Liquid Thermal Conductivity

Normally, liquid thermal conductivity is quite well behaved. The liquid thermal conductivity at any temperature can be estimated if the corresponding values at normal boiling temperature is known. Reid et al. (1977) suggested a correlation for non-polar fluids relating the thermal conductivity to that at normal boiling point;

$$\lambda_L = \frac{2.64 \times 10^{-3}}{M} \left[\frac{3 + 20(1 - T_r)^{2/3}}{3 + 20(1 - T_{rb})^{2/3}} \right] \quad (\text{B.33})$$

where T_{rb} is the reduced normal boiling temperature. Thermal conductivity evaluated from equation (B.33) has a unit of *cal/cm.s.K*. For $T_r > 0.8$, the equation for high density gas thermal conductivity (equation (B.32)) can be used.

Surface Tension

Reid et al. (1977) modified the equation suggested by Brock and Bird (1955) for the surface tension evaluation. The modified equation relates the surface tension to

the normal boiling temperature of the substance. Their equation is shown below.

$$\begin{aligned}\sigma &= P_c^{2/3} T_c^{1/3} \theta (1 - T_r)^{11/9} \\ \theta &= 0.1207 \left[1 + \frac{T_{rb} \ln P_c}{(1 - T_{rb})} \right] - 0.281\end{aligned}\quad (\text{B.34})$$

where P_c is in atm. and T_c in Kelvins. Reid et al. (1977) reported an average error of less than 5% based on their comparison with experimental data.

Criterion for Dense Gas

In evaluating the transport properties for gases, different correlations are used for low and high density gases. A criterion is needed for deciding whether the gas is at low density or high density. Childs and Hanley (1968) have deduced criterion which indicates whether or not the pressure effect is significant. Their results are summarized in figure B8. An approximate equation for the above criterion is

$$P_r = -0.125 + 0.1875 T_r \quad (\text{B.35})$$

Equation (B.35) is used to separate low density gases from high density gases.

Accuracy of Non-Aqueous Property Code

All the above mentioned equations were used in the development of the property code for non-aqueous fluids. This code is generally applicable to non-polar fluids with adequate accuracy. Data for Carbon dioxide, Nitrogen, and Freon-12 were used to test the accuracy of the property code. The predictions for all properties are very accurate for gases as expected. Results of the comparison for Freon-12 are shown in figures B9 to B13. For the saturated liquid properties, deviations of more than 10% are found at temperatures close to T_c . More extensive numerical comparison was made and the results are summarized in Table B-3. The results indicate that the property code developed can predict the thermodynamic and transport properties of non-polar fluids satisfactorily. With the availability of new and more accurate correlations, this property code can be updated easily to produce more accurate predictions.

Programming Specifications of the Property Code

The code is written in modular form for easy updating of new equations. Flowcharts for the property code are summarized in figures B14 to B15. The source code is shown in figure B17. The code is written in Fortran-77 language and compiled with IBM Professional Fortran Compiler. It is available in micro-computer version and would require an 8087 Math Coprocessor. The required input parameters are the critical constants (T_c , P_c and V_c), molecular weight (M), acentric factor (ω) constants for ideal gas specific heat (CPVA, CPVB, CPVC and CPVD) and constants for liquid viscosity (B and T^0). A list of such constants for several commonly used fluids is shown in table B-4.

Table B-1. Comparison of Calculated Thermodynamic Properties with Pitzer's Table for a Total of 2640 Data Points at 22 T_r and 20 P_r Conditions

Acentric factor	Average absolute deviation				
	Z				
	SRK	PR	HK	ICL	THIS WORK
0.0	0.011	0.026	0.013	0.042	0.007
0.1	0.018	0.018	0.016	0.043	0.007
0.2	0.026	0.013	0.019	0.043	0.010
0.3	0.033	0.013	0.022	0.044	0.013
0.4	0.041	0.017	0.025	0.045	0.017
0.5	0.049	0.025	0.028	0.047	0.022
overall	0.030	0.019	0.020	0.047	0.013

Acentric factor	$\log (f/p)$				
	SRK	PR	HK	ICL	THIS WORK
	SRK	PR	HK	ICL	THIS WORK
0.0	0.005	0.016	0.005	0.016	0.004
0.1	0.009	0.012	0.005	0.015	0.003
0.2	0.012	0.008	0.006	0.014	0.004
0.3	0.016	0.005	0.007	0.014	0.006
0.4	0.019	0.007	0.008	0.015	0.008
0.5	0.022	0.010	0.009	0.016	0.011
overall	0.014	0.010	0.007	0.015	0.006

Acentric factor	$(H^o-H)_T/RT_c$				
	SRK	PR	HK	ICL	THIS WORK
	SRK	PR	HK	ICL	THIS WORK
0.0	0.041	0.079	0.077	0.065	0.047
0.1	0.044	0.057	0.080	0.049	0.040
0.2	0.059	0.046	0.089	0.054	0.040
0.3	0.085	0.053	0.099	0.080	0.051
0.4	0.120	0.073	0.114	0.126	0.067
0.5	0.159	0.104	0.131	0.183	0.089
overall	0.085	0.069	0.098	0.093	0.056

SRK — Soave (1972)
PR — Peng-Robinson (1976)
HK — Harmens and Knapp (1980)
ICL — Ishikawa et al. (1980)
THIS WORK — Adachi et al. (1983)

Table B-2. Comparison of Calculated and Experimental Values of Three Saturated Properties

		Average absolute deviation %														
		SRK			PR			HK			ICL			This work		
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Methane	a 29	1.50	6.80	2.16	1.61	7.73	3.23	0.83	5.20	2.52	1.56	4.83	3.42	1.19	4.94	2.18
Ethane	a 27	1.12	13.6	3.32	1.07	6.68	2.24	0.47	6.76	1.41	1.48	5.08	1.75	1.08	8.46	1.40
Propane	a 31	1.40	13.6	0.77	1.02	5.75	2.25	0.72	5.75	1.70	1.30	3.80	1.73	1.14	6.62	1.78
n-Butane	a 28	1.46	13.3	1.05	0.95	4.65	1.49	0.62	4.72	1.24	1.10	3.52	2.15	1.12	4.75	1.46
n-Pentane	a 30	0.91	15.1	1.43	0.33	4.71	1.11	0.65	5.13	1.51	0.69	3.79	3.26	0.30	4.45	0.95
n-Hexane	a 30	1.75	18.4	1.50	1.00	5.38	1.05	0.90	5.14	1.62	0.83	3.09	5.21	1.03	5.72	0.97
n-Heptane	b 21	1.51	19.7	1.76	0.74	6.11	1.04	1.30	5.42	1.96	2.33	3.77	7.48	0.68	5.09	0.98
n-Octane	b 18	1.63	21.9	1.94	0.93	7.91	1.04	0.82	4.64	2.34	2.32	3.46	8.68	0.66	5.18	1.16
n-Nonane	c 13	1.70	16.9	-	2.31	3.41	-	2.51	3.97	-	8.72	6.28	-	2.39	1.25	-
n-Decane	c 7	5.79	19.6	-	4.90	5.94	-	6.31	2.62	-	15.0	5.47	-	4.81	0.86	-
Oxygen	a 24	1.01	4.44	3.38	0.63	7.96	3.95	0.90	4.84	4.19	0.79	4.67	3.23	0.41	2.79	3.61
Nitrogen	a 18	1.30	6.40	2.77	1.39	8.12	4.33	0.54	5.73	3.07	1.56	5.18	4.18	1.23	4.20	3.36
Carbon-monoxide	a 24	0.83	3.83	3.87	1.43	8.49	2.97	1.08	5.35	3.67	1.59	5.46	3.05	1.04	2.41	3.04
Carbon-dioxide	a 32	0.40	14.5	1.74	0.67	4.62	1.30	0.88	4.84	1.53	0.91	3.43	3.54	0.57	4.69	1.11
Ethylene	a 21	1.55	7.49	2.42	1.14	6.59	1.60	1.41	4.87	2.51	1.25	4.42	1.32	1.12	3.31	1.79
Propylene	a 26	1.06	10.3	2.15	0.60	5.26	1.41	1.09	4.77	1.99	0.48	3.87	1.78	0.52	3.61	1.43
1-Butene	a 26	1.24	12.2	1.36	0.67	4.41	2.02	0.45	4.43	2.12	0.82	3.72	1.54	0.84	3.86	1.81
Acetylene	a 22	2.01	12.5	1.04	1.55	5.00	0.97	1.46	4.99	1.25	1.45	3.89	1.56	1.73	4.54	0.77
Overall		1.57	12.8	2.04	1.28	6.04	2.00	1.27	4.96	2.17	2.45	4.32	3.37	1.21	4.26	1.78

a Canjar and Manning (1967)

b Young (1910)

c Sage and Lacey (1950, 1955)

A $\Delta P/P$ N Number of data points

B $\Delta V^L/V^L$

C $\Delta V^V/V^V$

SRK — Soave (1972)

PR — Peng-Robinson (1976)

HK — Harmens and Knapp (1980)

ICL — Ishikawa et al. (1980)

THIS WORK — Adachi et al. (1983)

Table B-3. Summary of Fluid Property Prediction Accuracy for Different Fluids

Fluid Property	Freon-12		Nitrogen		Carbon Dioxide	
	N	RMS*	N	RMS*	N	RMS*
Sat. Liq. Vol.	24	0.0665	20	0.0519	19	0.0727
Sat. Vap. Vol.	24	0.0108	20	0.0160	19	0.0084
Superheated Vap. Vol.	35	0.0079	22	0.0026	55	0.0064
Sat. Liq. Enthalpy	24	0.0560	20	0.1487	18	0.0981
Sat. Vap. Enthalpy	24	0.0211	20	0.1180	18	0.0139
H _{fg}	24	0.0338	20	0.0444	18	0.0605
Superheated Enthalpy	35	0.0110	22	0.0166	55	0.0126
Sat. Liq. Sp. Heat	14	0.1058	11	0.1701	9	0.1291
Sat. Vap. Sp. Heat	14	0.1097	11	0.0379	9	0.1381
Superheated Sp. Heat	40	0.0254	22	0.0127	35	0.0047
Sat. Liq. Viscosity	14	0.1789	12	0.1097	7	0.0531
Sat. Vap. Viscosity	14	0.0812	12	0.0213	7	0.0202
Superheated Viscosity	24	0.0535	26	0.0081	23	0.0166
Sat. Liq. Therm. Cond.	15	0.1402	14	0.1111	13	0.0744
Sat. Vap. Therm. Cond.	15	0.0863	14	0.0957	13	0.0968
Superheated Therm. Cond.	24	0.0408	26	0.0503	31	0.0467
Overall Average	364	0.0643	292	0.0634	349	0.0533

* RMS error is defined as

$$RMS = \sqrt{\frac{(\text{Error}_{\text{pred}})^2}{N}}$$

Table B-4. List of Constant Necessary for Property Evaluation

	FREON-11	FREON-12	FREON-13	FREON-21	FREON-22
CRITICAL TEMP. (DEG. K)	471.2	385.0	302.0	451.6	369.2
CRITICAL PRESS. (PASCAL)	4406550	4122910	3920310	5166300	4973830
CRITICAL VOLUME (M**3/KG)	1.805E-3	1.795E-3	1.723E-3	1.914E-3	1.906E-3
ACCENTRIC FACTOR	0.188	0.176	0.180	0.202	0.215
MOLECULAR WEIGHT	137.368	120.914	104.459	102.923	86.469
CONSTANTS FOR IDEAL GAS CP.					
CPVA	9.789	7.547	5.449	5.652	4.132
CPVB	3.893E-2	4.257E-2	4.565E-2	3.777E-2	3.865E-2
CPVC	-3.383E-5	-3.603E-5	-3.765E-5	-2.866E-5	-2.794E-5
CPVD	9.903E-9	1.037E-8	1.065E-8	7.795E-9	7.305E-9
CONSTANTS FOR LIQUID VISC.					
BO	840.17	684.0	564.472	731.876	532.853
TO	227.9	178.7	138.315	203.167	176.928

SUBCOOLED

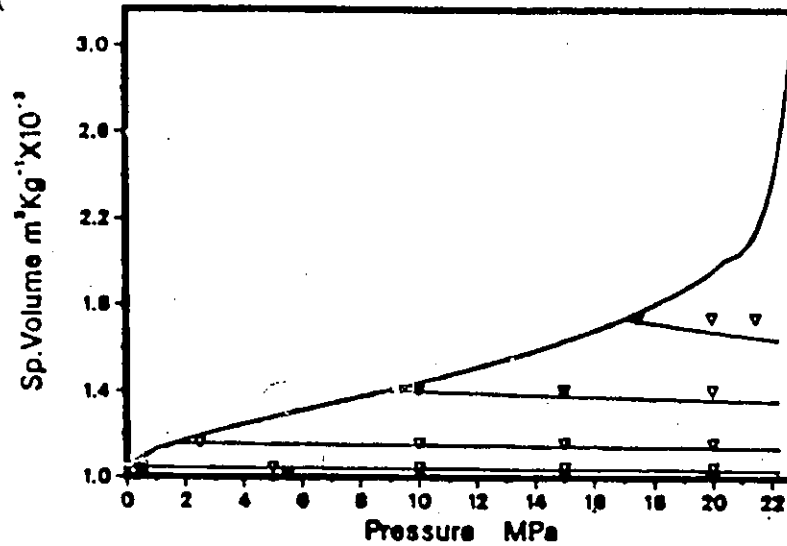


Figure B1a. Comparison of Subcooled Specific Volume Predicted from UOOCODE with Steam Table (ASME, 1967).

SUPERHEATED

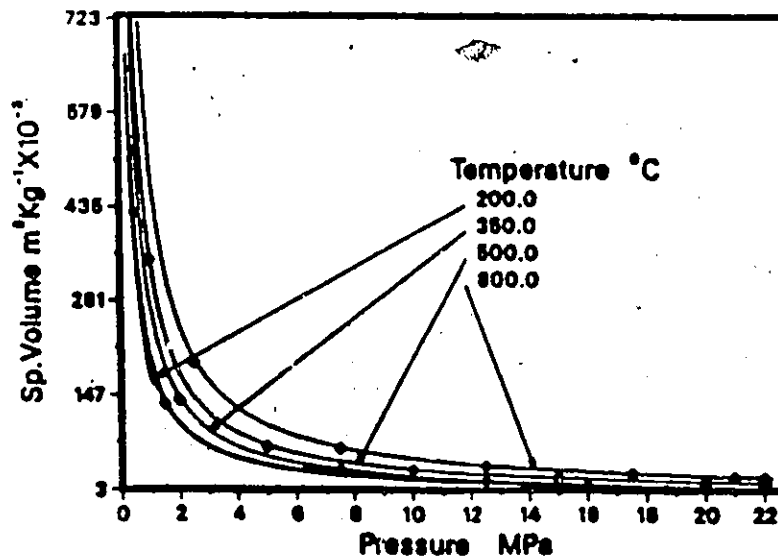


Figure B1b. Comparison of Superheated Specific Volume Predicted from UOOCODE with Steam Table (ASME, 1967).

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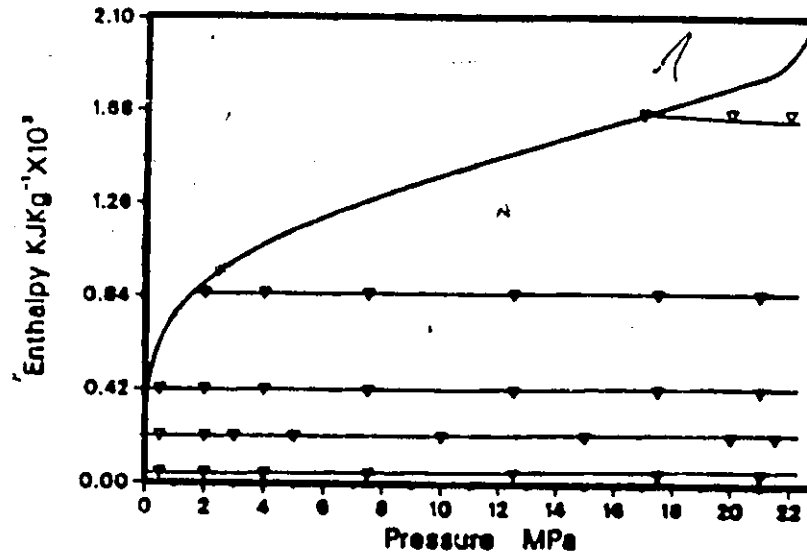


Figure B2a. Comparison of Subcooled Enthalpy Predicted from UOCODE with Steam Table (ASME, 1967).

SUPERHEATED

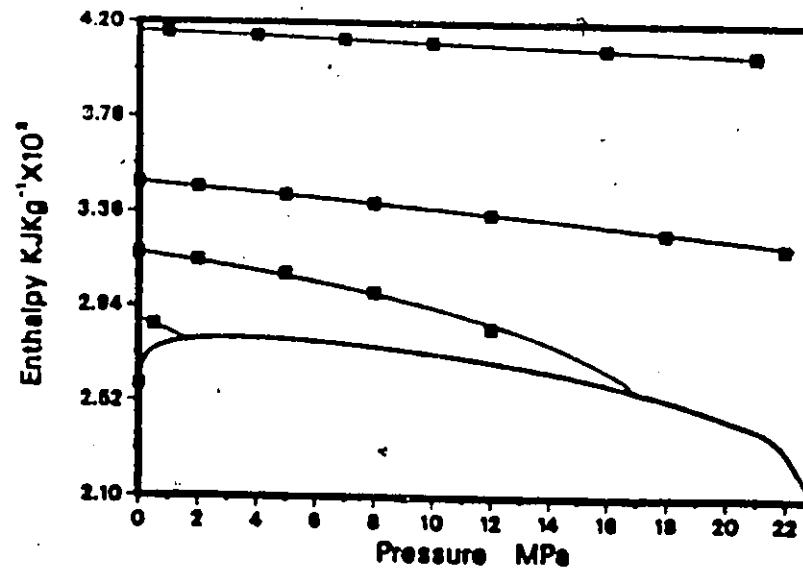


Figure B2b. Comparison of Superheated Enthalpy Predicted from UOCODE with Steam Table (ASME, 1967).

SUBCOOLED

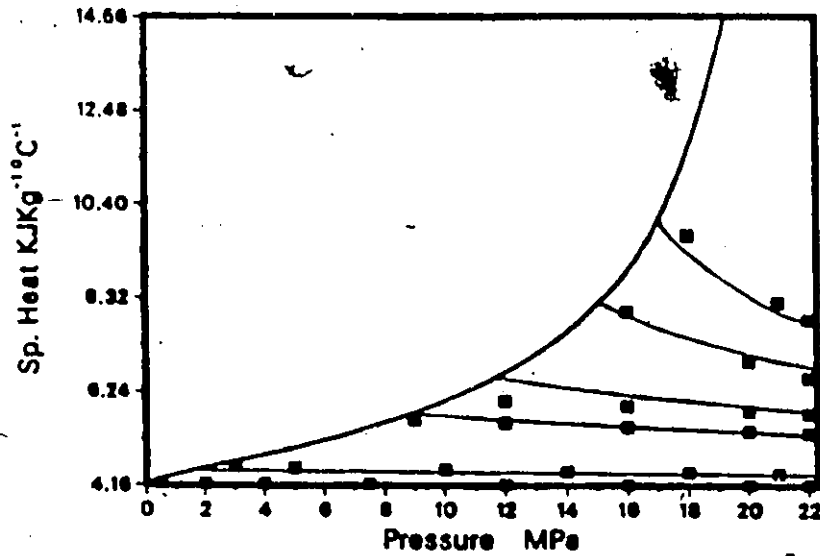


Figure B3a. Comparison of Subcooled Specific Heat Predicted from UOCCODE with Steam Table (ASME, 1967).

SUPERHEATED

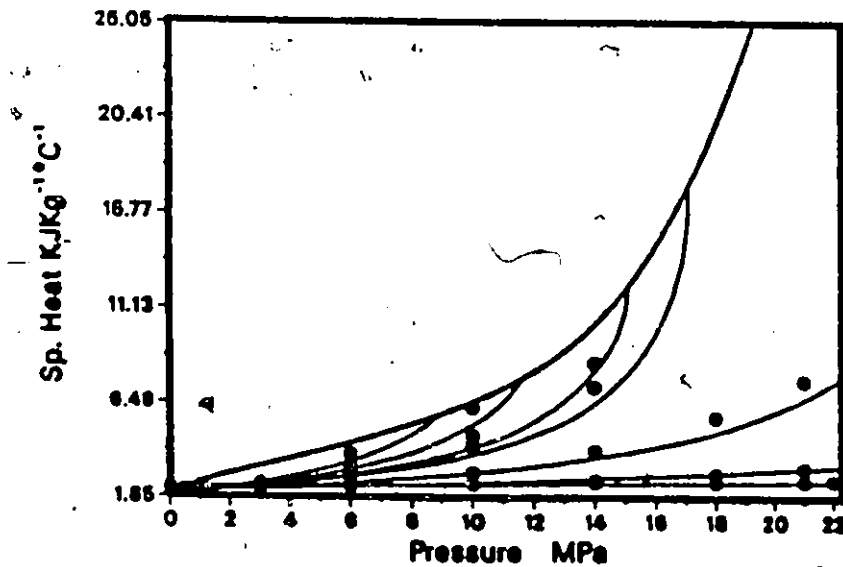


Figure B3b. Comparison of Superheated Specific Heat Predicted from UOCCODE with Steam Table (ASME, 1967).

SUBCOOLED

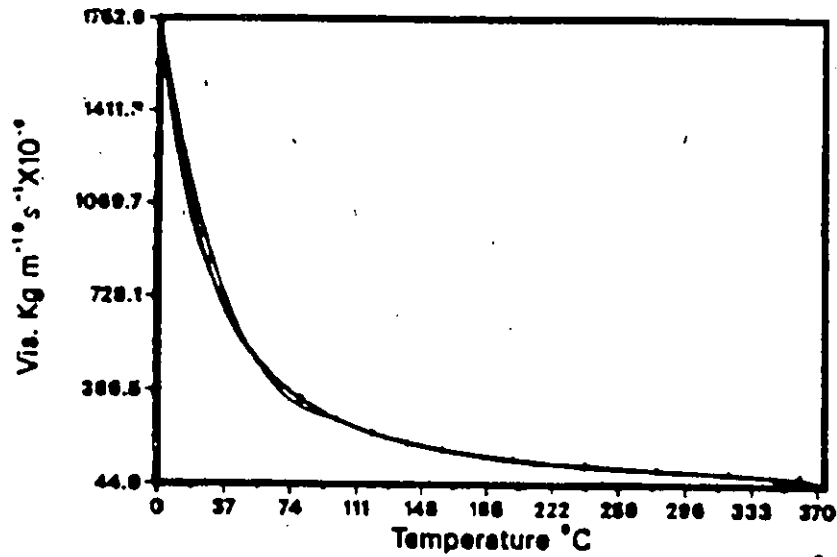


Figure B4a. Comparison of Subcooled Viscosity Predicted from UOOCODE with Steam Table (ASME, 1967).

SUPERHEATED

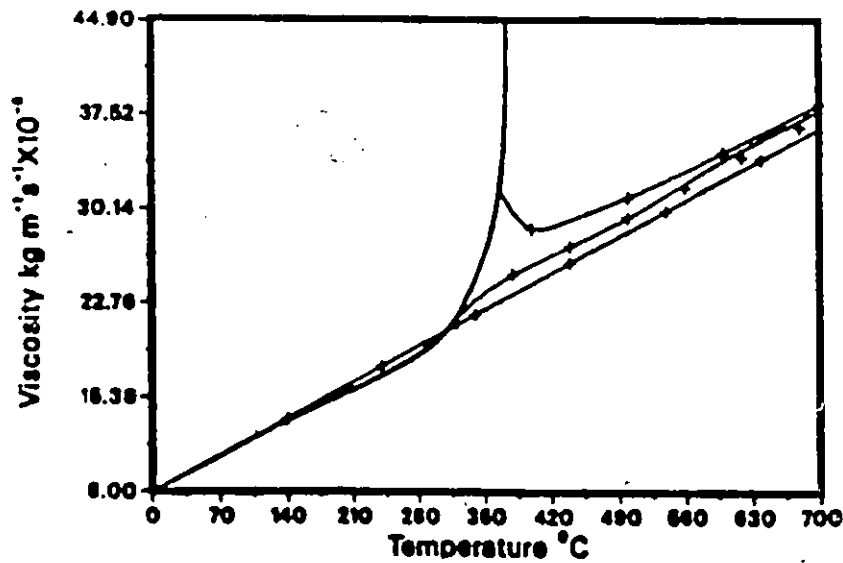


Figure B4b. Comparison of Superheated Viscosity Predicted from UOOCODE with Steam Table (ASME, 1967).

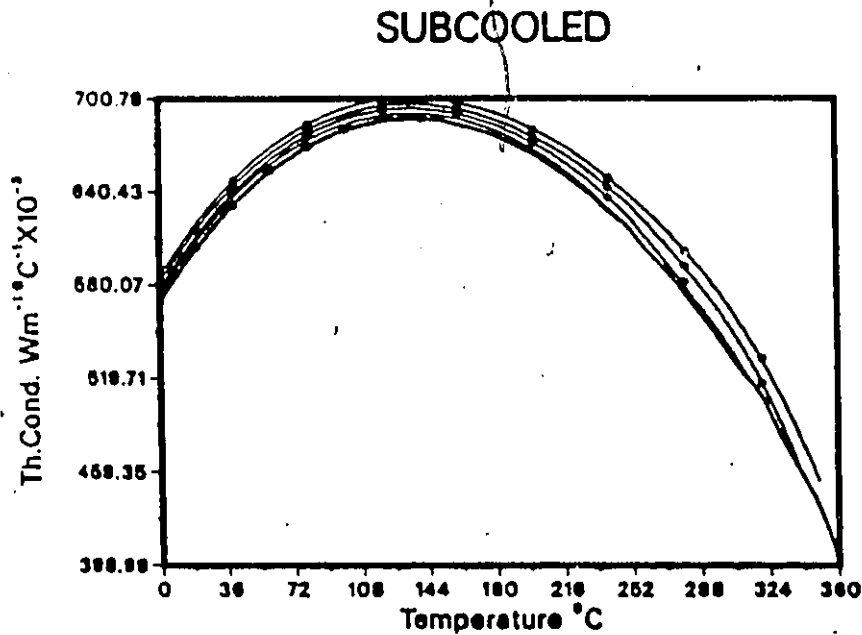


Figure B5a. Comparison of Subcooled Thermal Conductivity Predicted from UOOCODE with Steam Table (ASME, 1967).

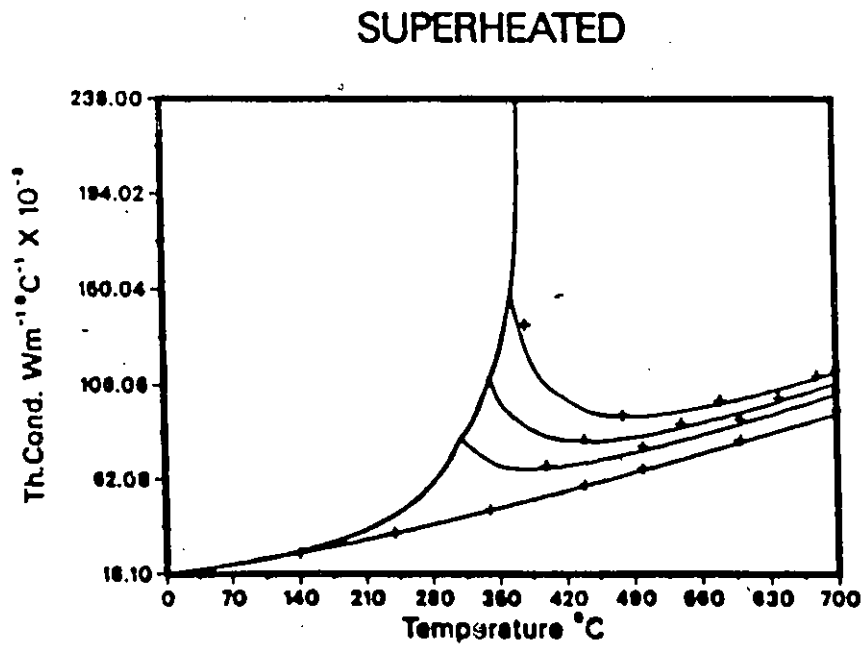


Figure B5b. Comparison of Superheated Thermal Conductivity Predicted from UOOCODE with Steam Table (ASME, 1967).

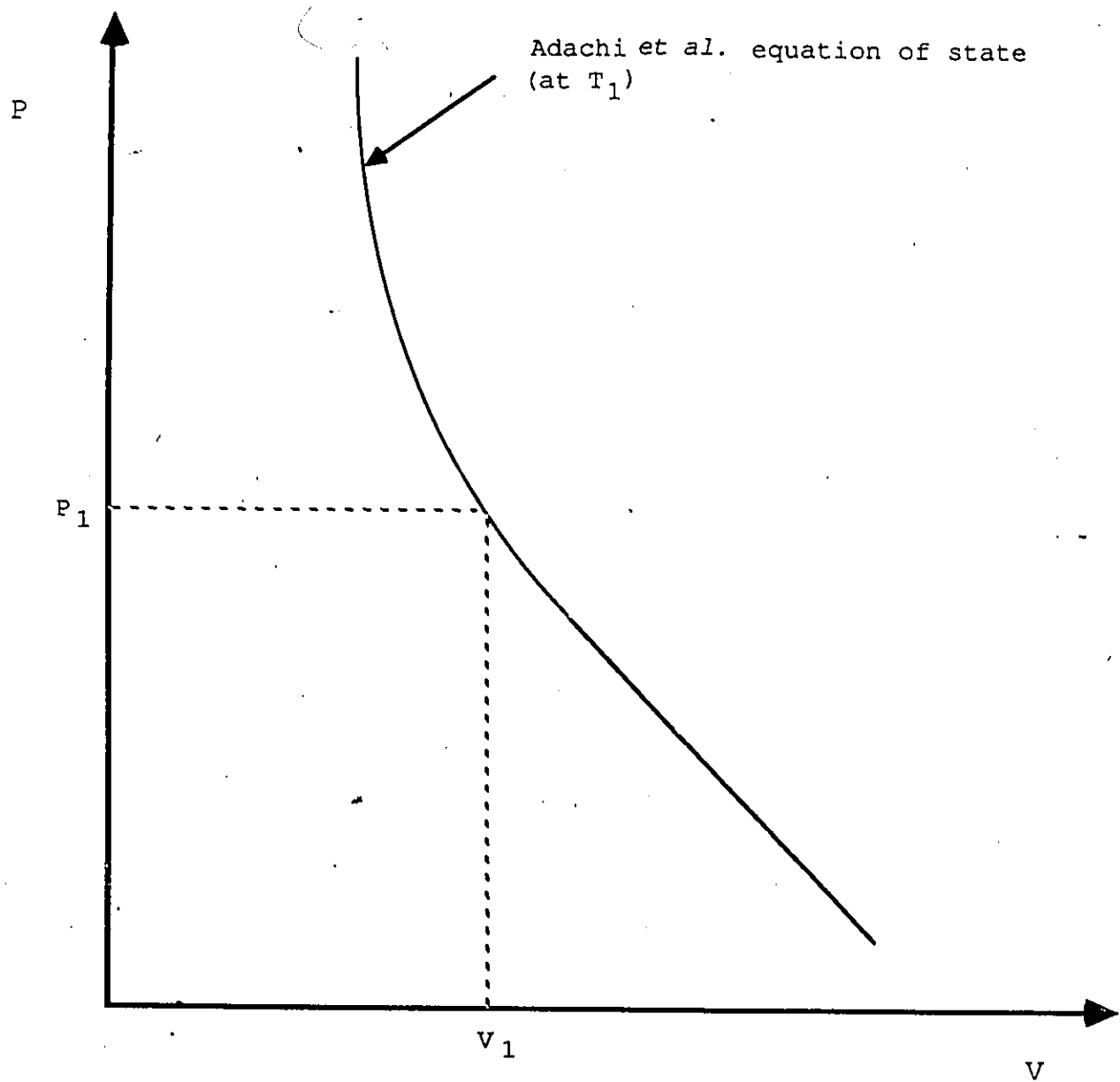


Figure B6. P-V-T Relation for a Typical Fluid at Superheated State.

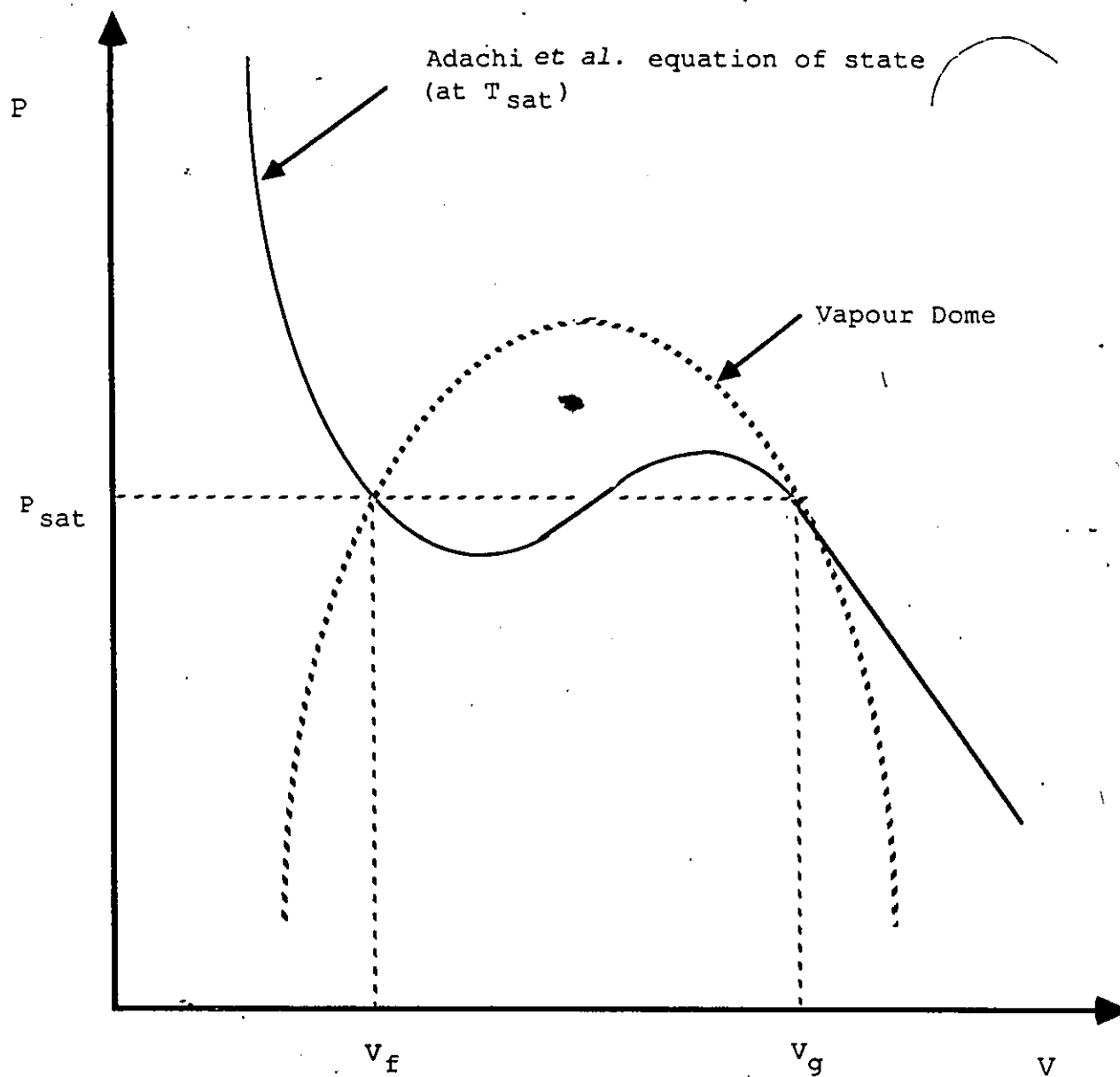


Figure B7. P-V-T Relation for a Typical Fluid at Saturation State.

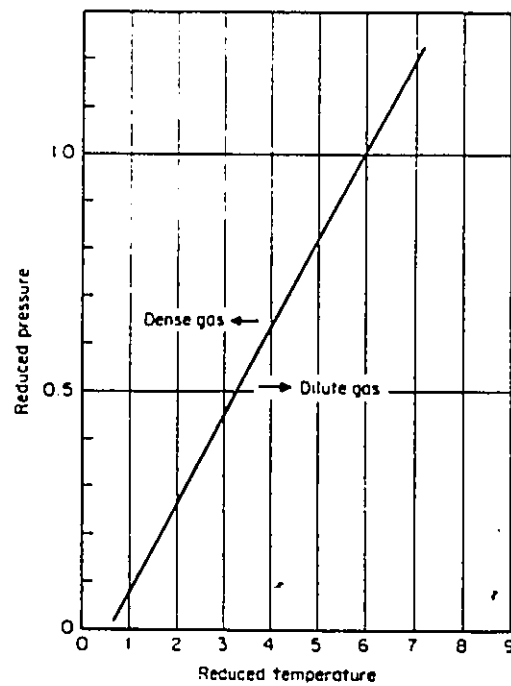


Figure B8. Criterion for Dense Gas (Childs and Hanley, 1968).

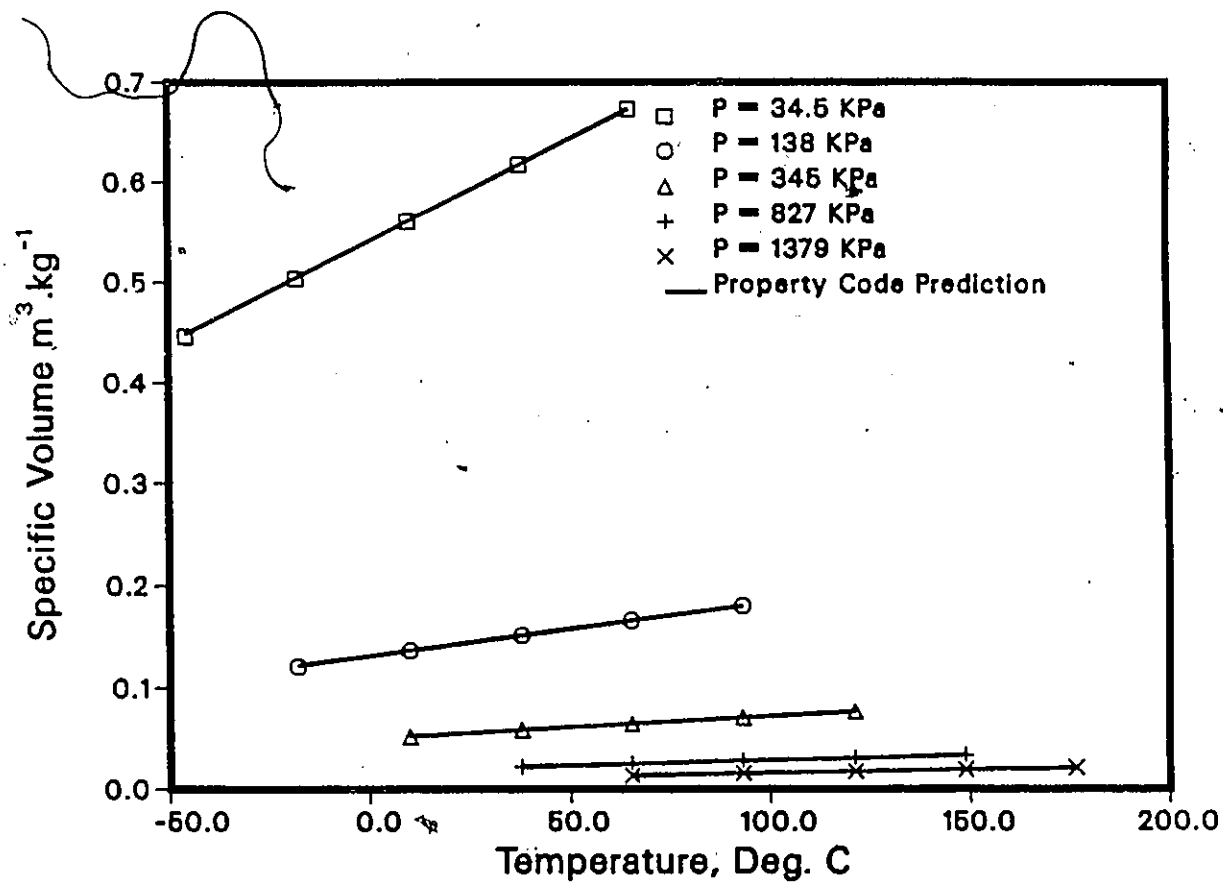


Fig. B9a. Comparison of Specific Volume Predicted from Non-Aqueous property Code with Freon-12 Data at Superheated State.

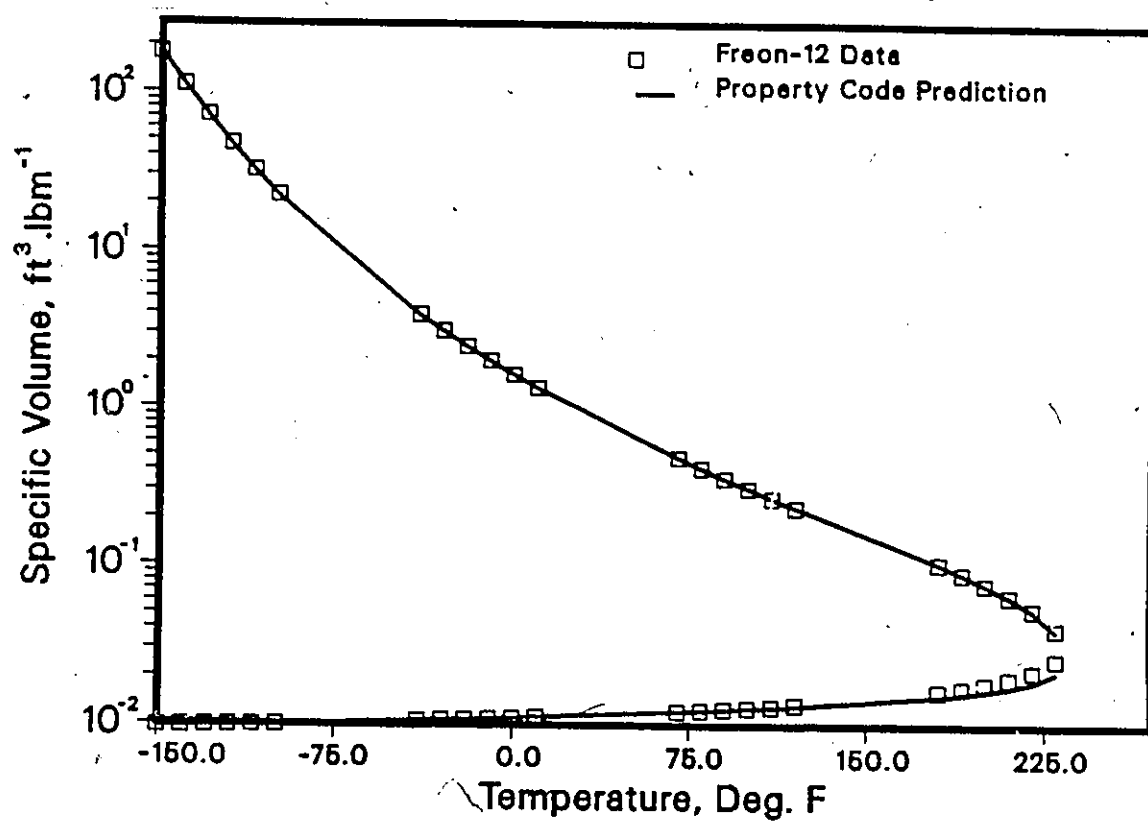


Fig B9b. Comparison of Specific Volume Predicted from Non-Aqueous Property Code with Freon-12 Data at Saturation State.

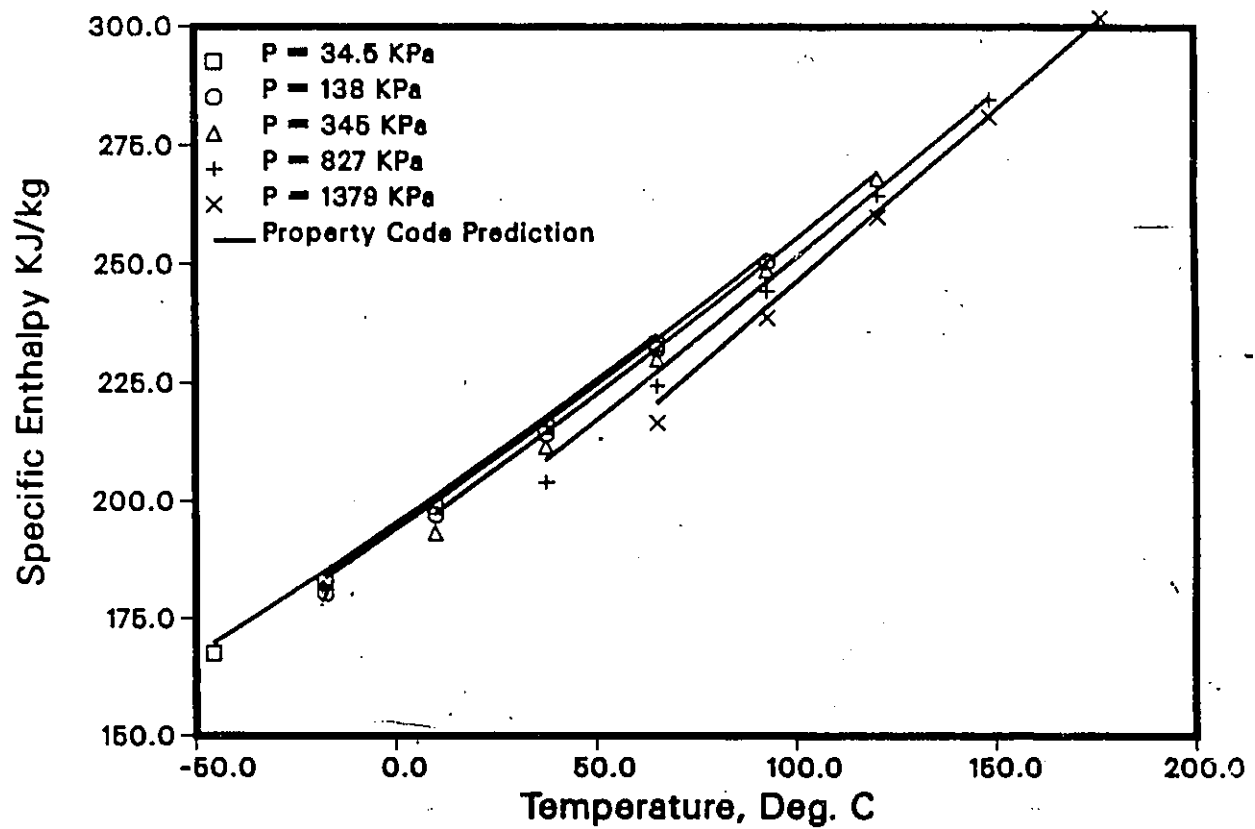


Fig. B10a. Comparison of Specific Enthalpy Predicted from Non-Aqueous property Code with Freon-12 Data at Superheated State.

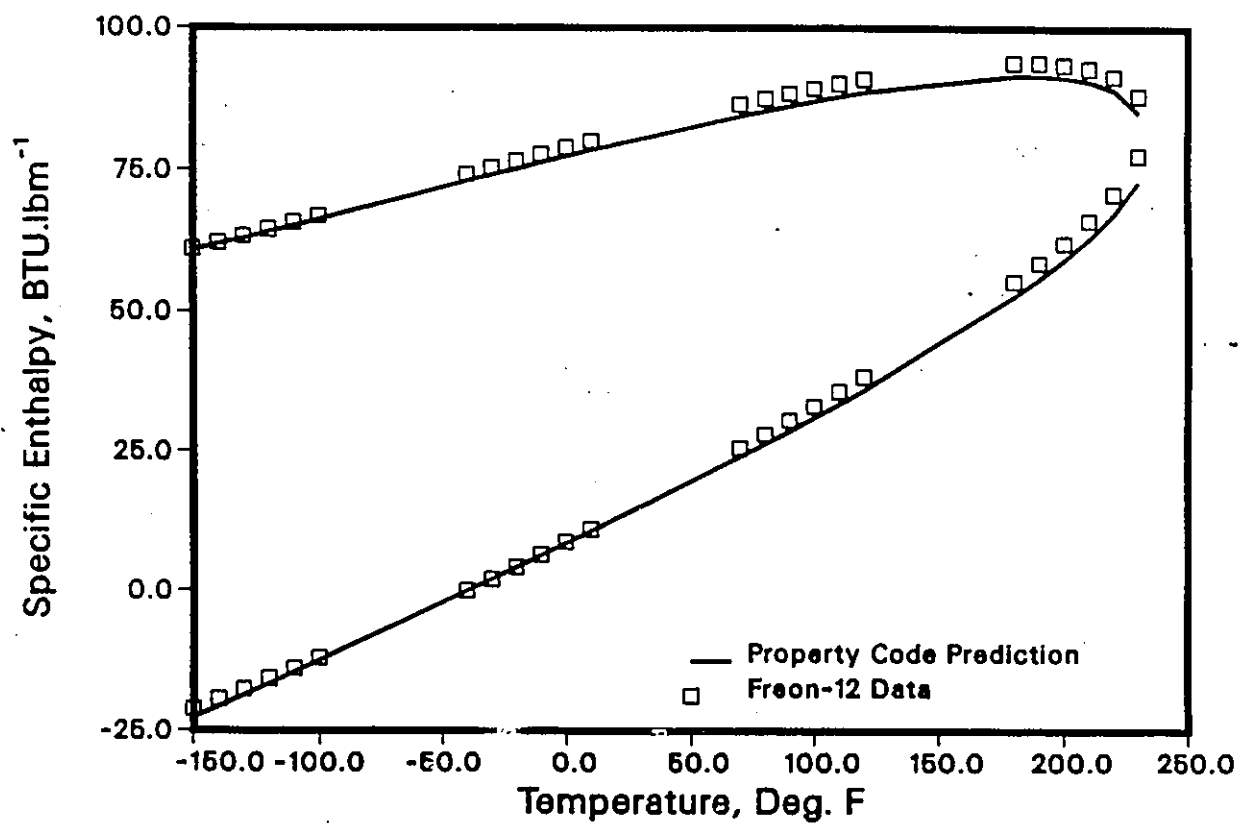


Fig B10b. Comparison of Specific Enthalpy Predicted from Non-Aqueous Property Code with Freon-12 Data at Saturation State.

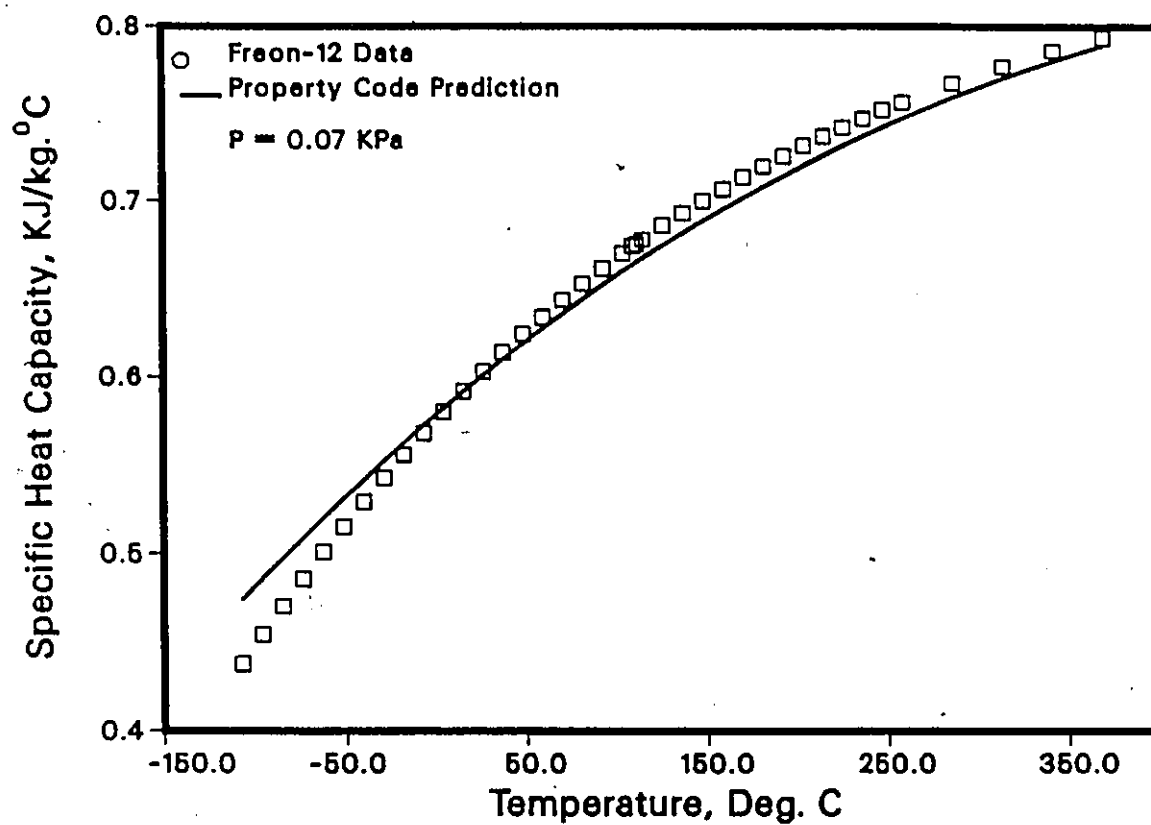


Fig B11a. Comparison of Specific Heat Capacity Predicted from Non-Aqueous Property Code with Freon-12 Data at Superheated State.

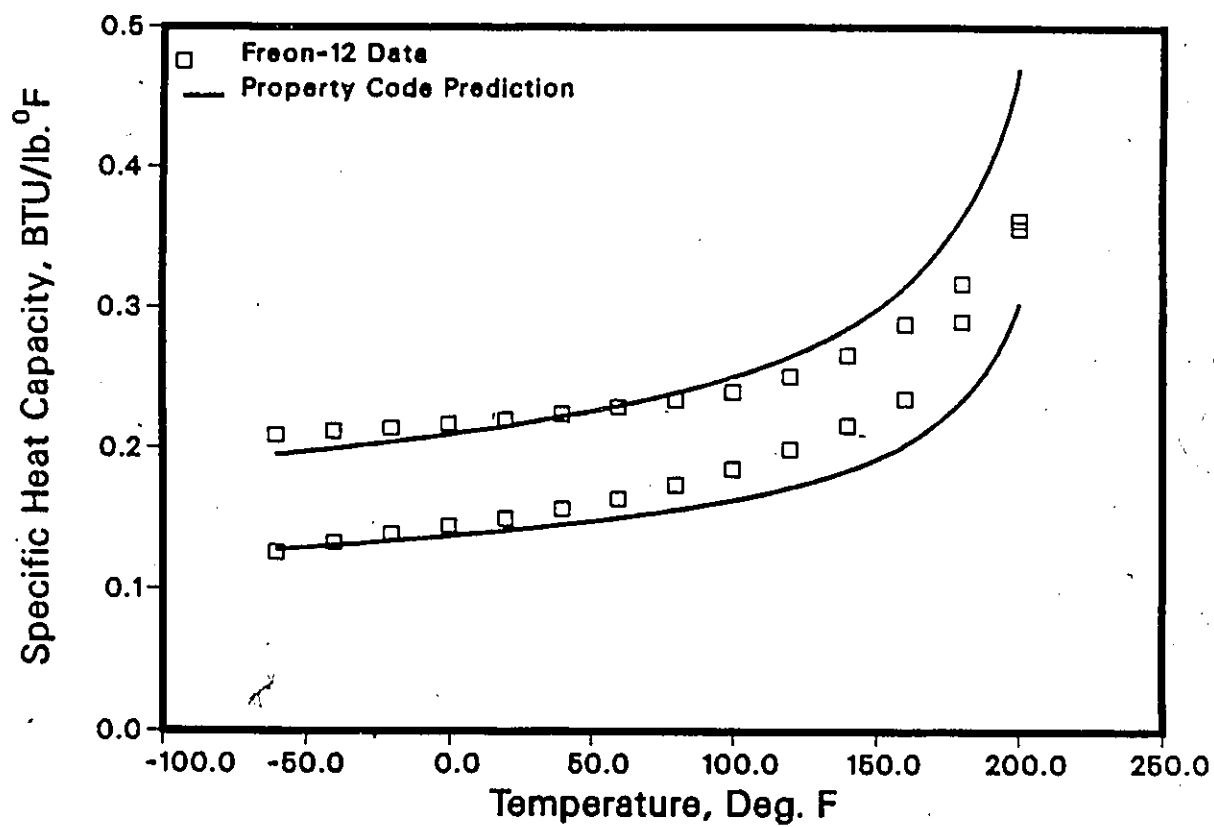


Fig. B11b. Comparison of Specific Heat Predicted from Non-Aqueous Property Code with Freon-12 Data at Saturation State.

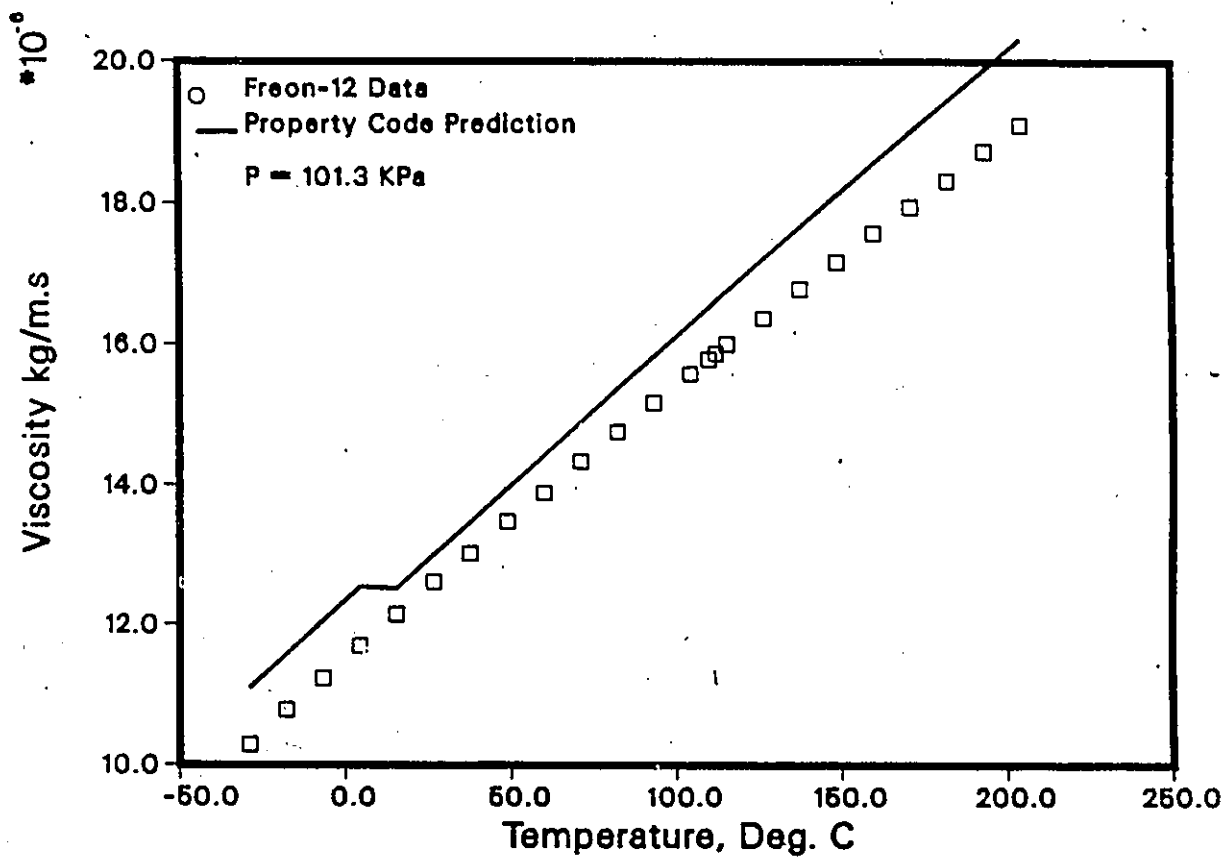


Fig. B12a. Comparison of Viscosity Predicted from Non-Aqueous Property Code with Freon-12 Data at Superheated State.

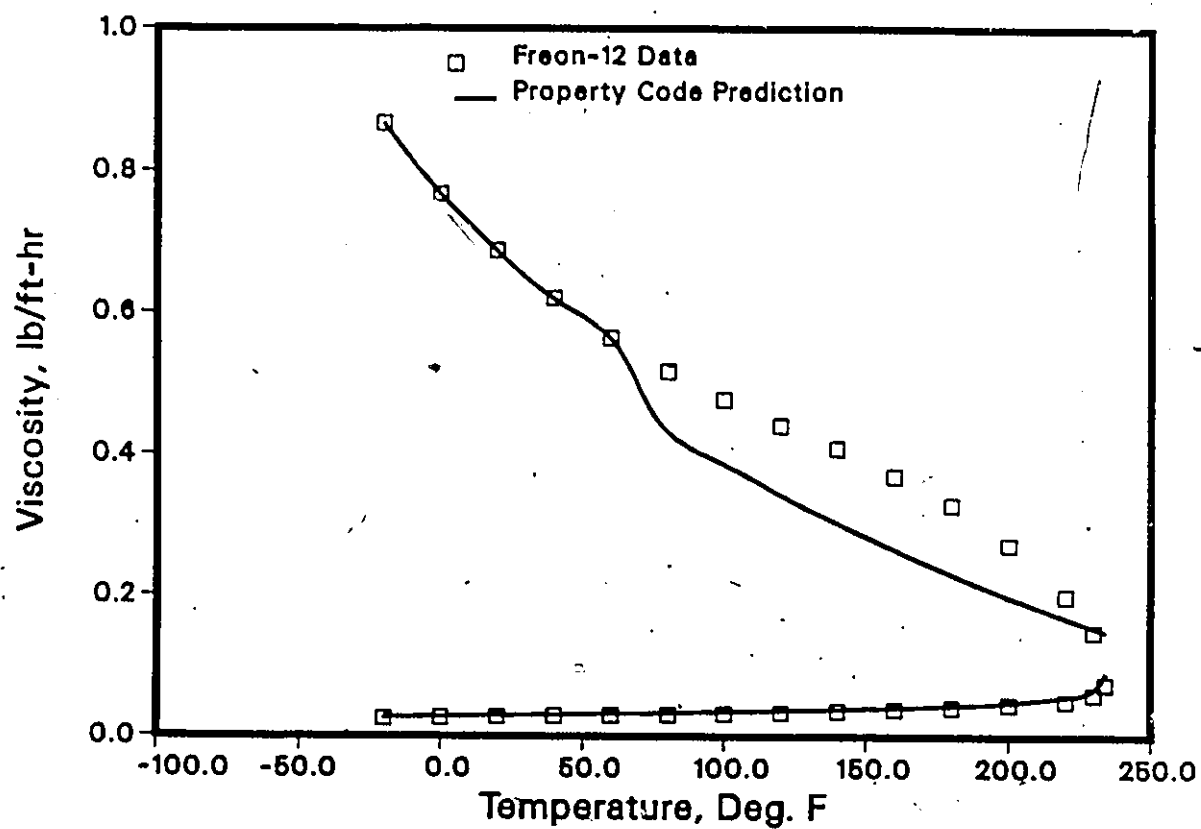


Fig B12b. Comparison of Viscosity Predicted from Non-Aqueous Property Code with Freon-12 Data at Saturation State.

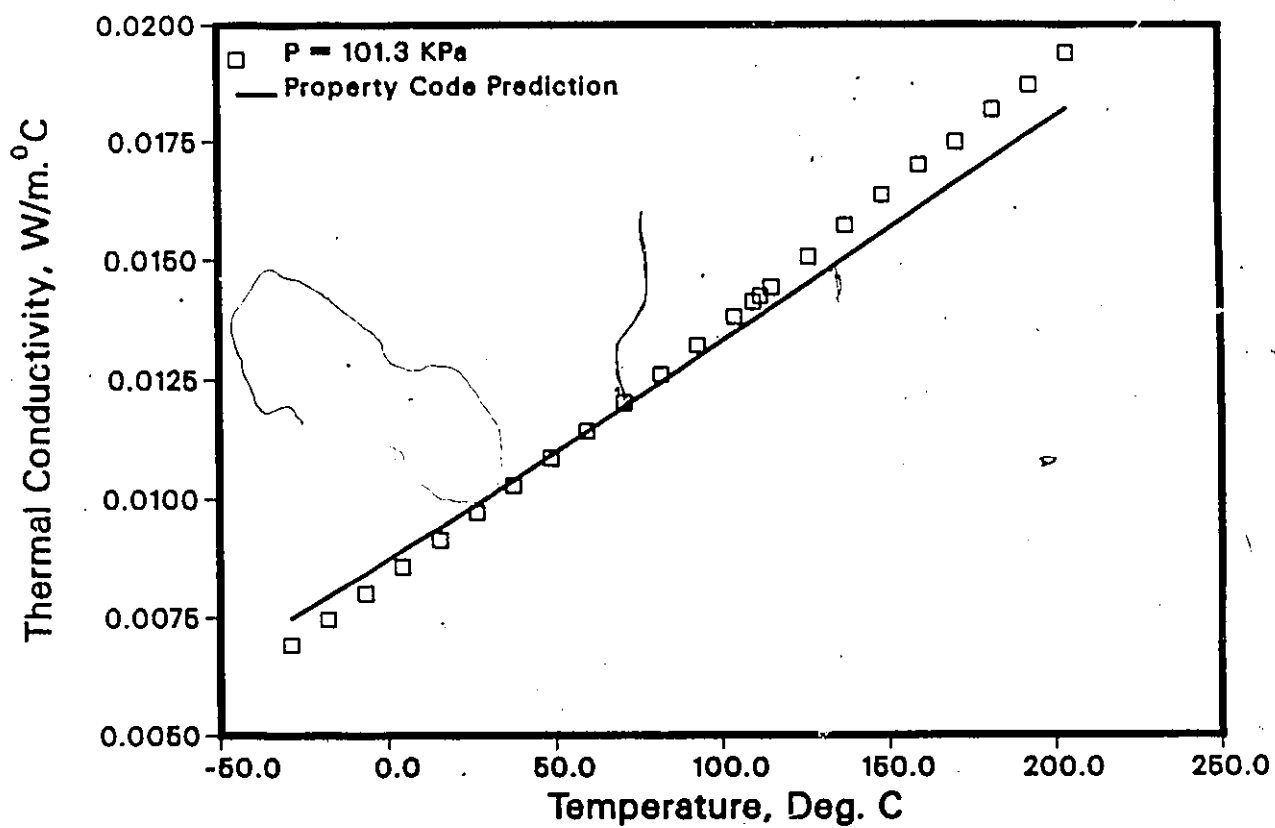


Fig. B13a. Comparison of Thermal Conductivity Predicted from Non-Aqueous property Code with Freon-12 Data at Superheated State.

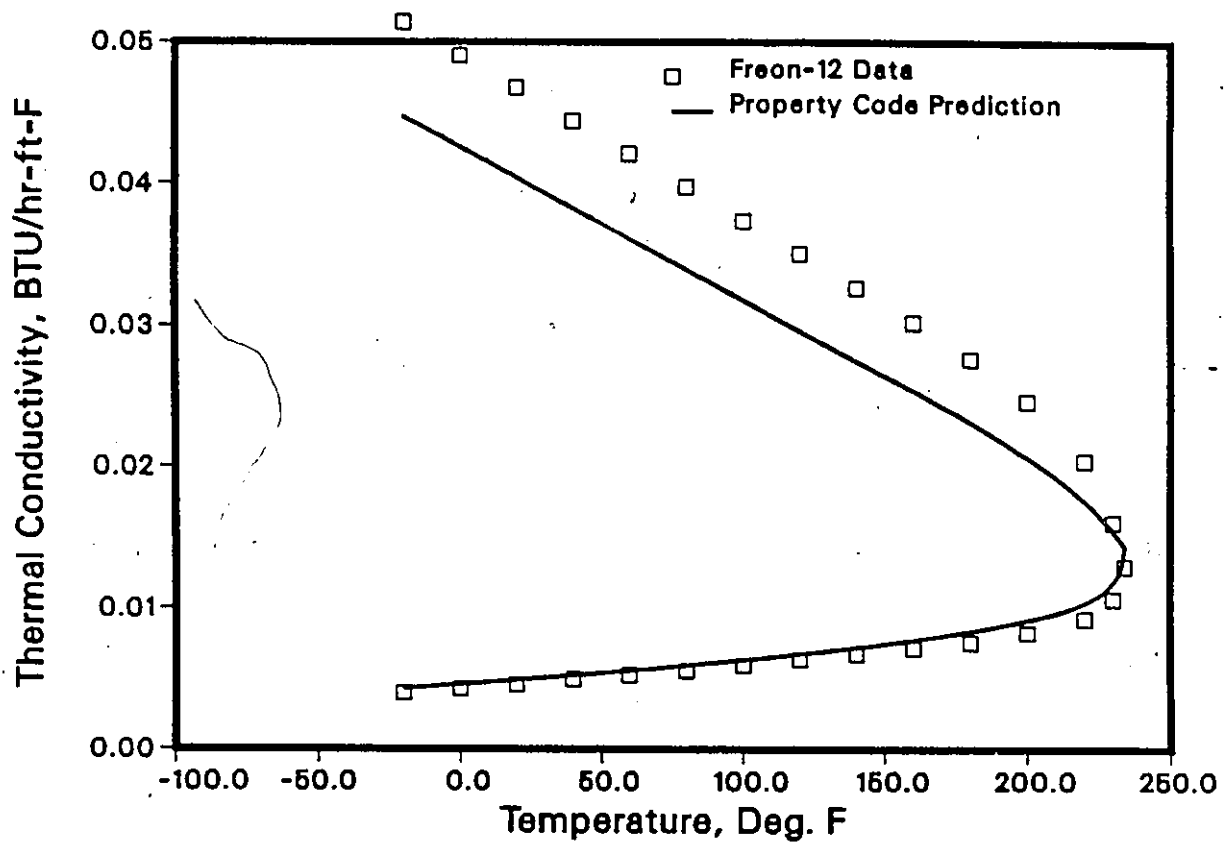


Fig B13b. Comparison of Thermal Conductivity Predicted from Non-Aqueous Property Code with Freon-12 Data at Saturation State.

LEVEL 1

Main Subroutine PROPER

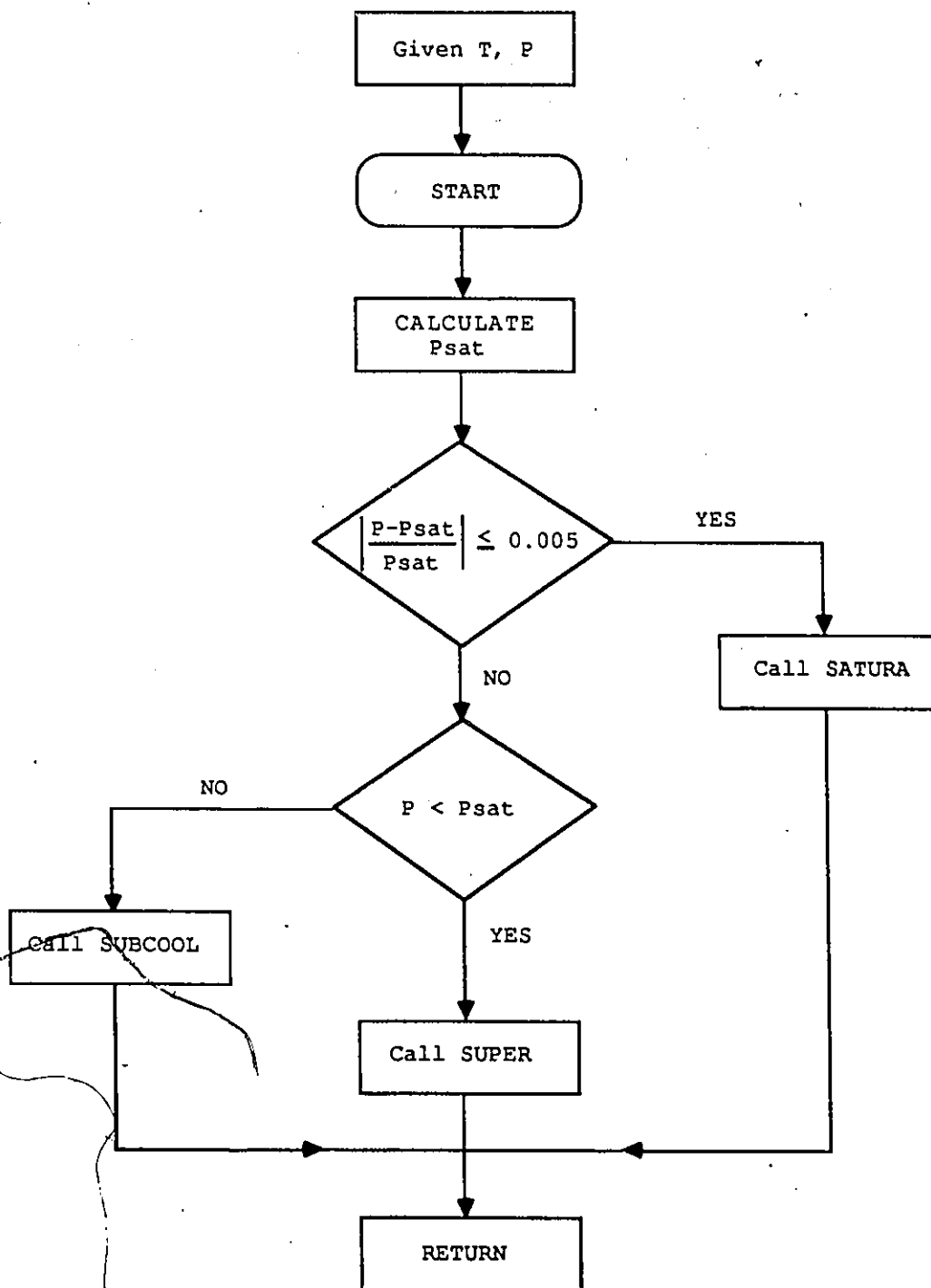


Figure B14. Flow-Chart for Main Program of Non-aqueous Property Code.

LEVEL 2

Subroutine SATURA

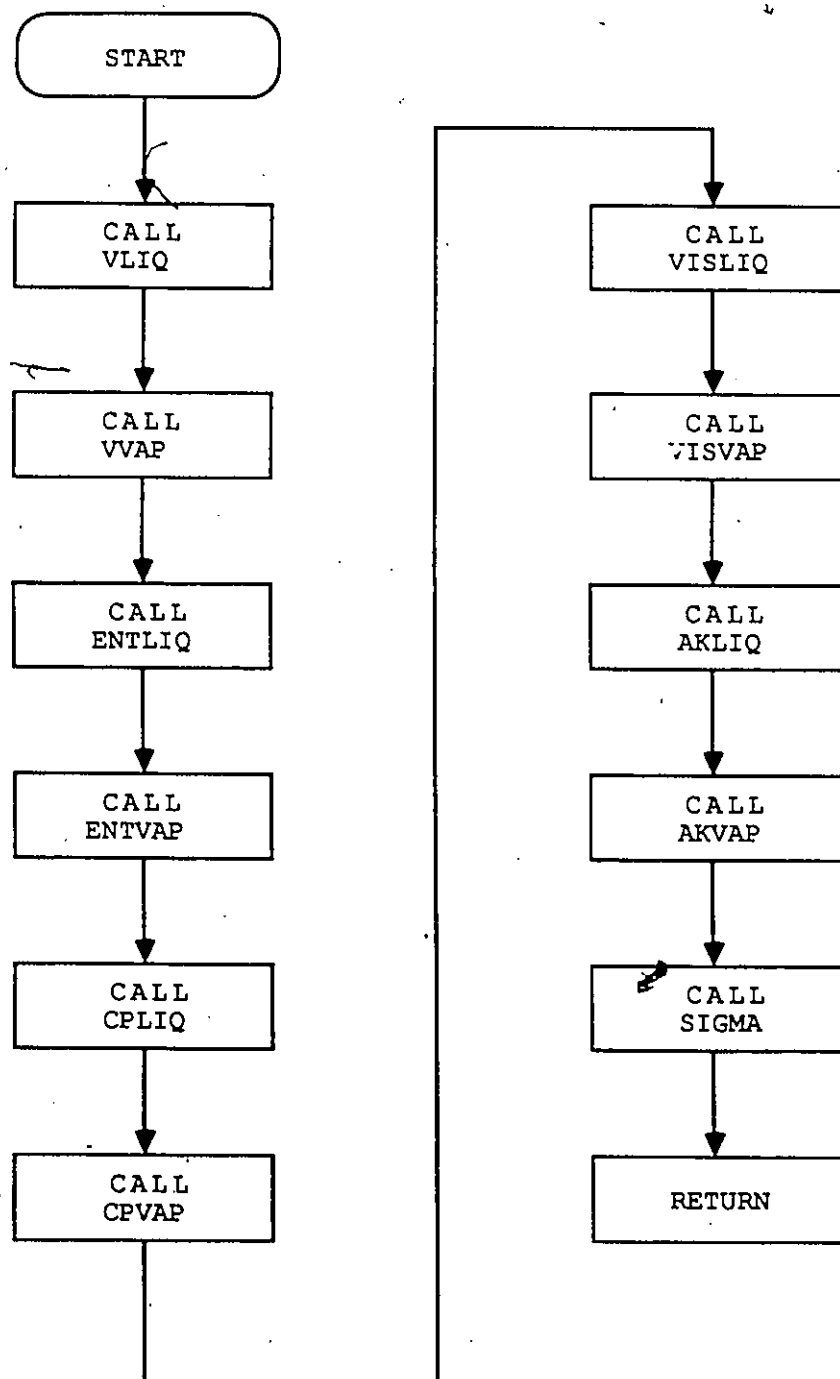
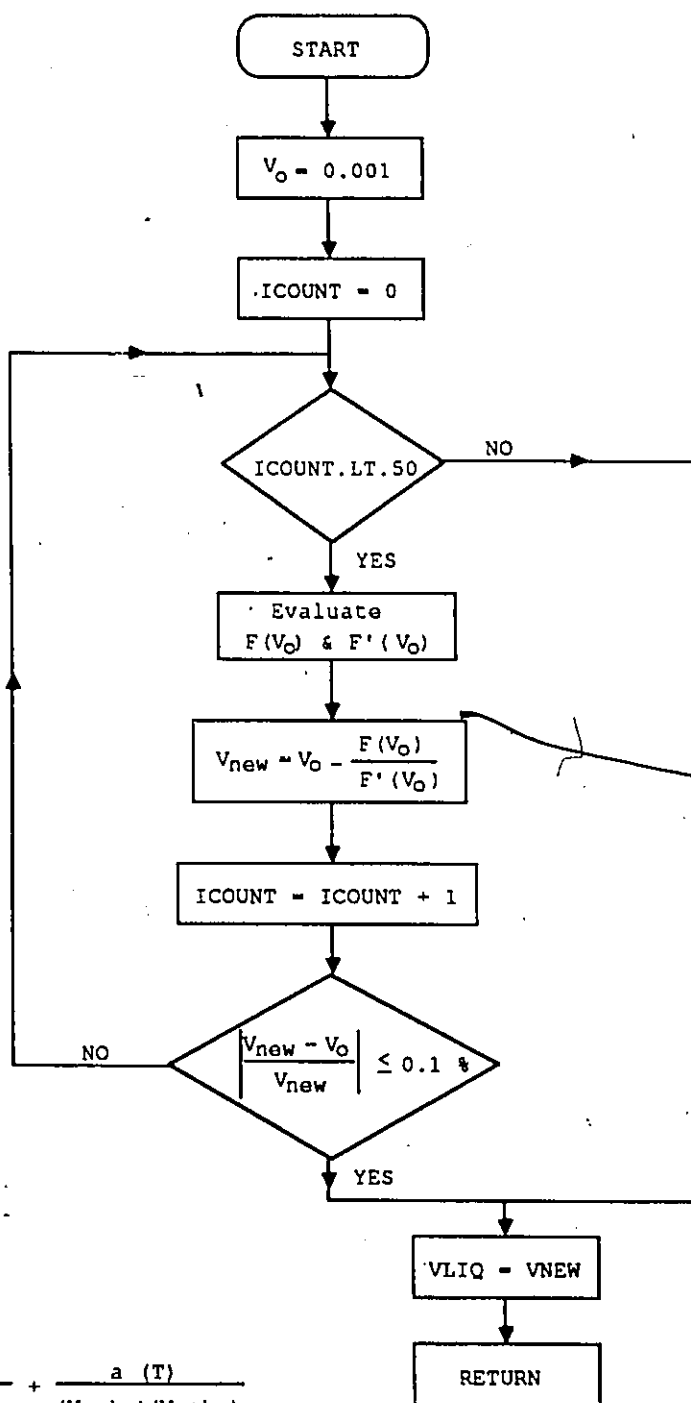


Figure B15. Flowchart for Saturation Subroutine.

LEVEL 3

Subroutine VLIO



$$F = P - \frac{RT}{V - b_1} + \frac{a(T)}{(V - b_2)(V + b_3)}$$

$$F' = \left. \frac{dF}{dV} \right|_{T,P}$$

Figure B16. Flowchart for Saturated Liquid Subroutine.

```

C
C*****
C
C   Subroutine for Non-Aqueous Fluid Property Evaluation
C   P = Pressure (Pa), T = Temperature (K).
C
C*****
C
C   SUBROUTINE PROPER(P,T)
C   REAL MW,MW1,MW2
C   DIMENSION B(3)
C
C*****
C
C   CRIT -   External Common block in which the physical constants
C            of the fluid are passed to this subroutine.
C
C   TC -     Critical temperature of the substance (K).
C   PC -     Critical pressure of the substance (Pa).
C   VC -     Critical volume of the substance (kg.m-3).
C   W -      Acentric factor of the substance.
C   MW -     Molecular weight of the substance (kg.kgmole-1).
C   CO1 -    First constant for ideal gas specific heat evaluation.
C   CO2 -    Second constant for ideal gas specific heat evaluation.
C   CO3 -    Third constant for ideal gas specific heat evaluation.
C   CO4 -    Fourth constant for ideal gas specific heat evaluation.
C            (constant values are given such that Cp0 has a unit of
C            cal.gmole-1.°C-1).
C   BO -     First constant for liquid viscosity evaluation.
C   TO -     Second constant for liquid viscosity evaluation.
C   TREF -   Reference temperature at which the saturated liquid
C            enthalpy is equal to zero.
C
C*****
C
C   COMMON /CRIT/TC,PC,VC,W,MW,CO1,CO2,CO3,CO4,BO,TO,TREF

```

Figure B17. Source Code for the Non-Aqueous Property Subroutine.

```

C
C*****
C
C  PROP  --- Common block in which all the calculated fluid
C           properties are passed back to the calling program.
C
C  VF -    Saturated liquid specific volume ( $\text{m}^3.\text{kg}^{-1}$ ).
C  VG -    Saturated vapour specific volume ( $\text{m}^3.\text{kg}^{-1}$ ).
C  VL -    Subcooled or superheated specific volume ( $\text{m}^3.\text{kg}^{-1}$ ).
C  RHOF -  Saturated liquid density ( $\text{kg}.\text{m}^{-3}$ ).
C  RHOG -  Saturated vapour density ( $\text{kg}.\text{m}^{-3}$ ).
C  RHOL -  Subcooled or superheated density ( $\text{kg}.\text{m}^{-3}$ ).
C  HF -    Saturated liquid enthalpy ( $\text{J}.\text{kg}^{-1}$ ).
C  HG -    Saturated vapour enthalpy ( $\text{J}.\text{kg}^{-1}$ ).
C  HL -    Subcooled or superheated enthalpy ( $\text{J}.\text{kg}^{-1}$ ).
C  CPF -   Saturated liquid specific heat capacity ( $\text{J}.\text{kg}^{-1}.\text{K}^{-1}$ ).
C  CPG -   Saturated vapour specific heat capacity ( $\text{J}.\text{kg}^{-1}.\text{K}^{-1}$ ).
C  CPL -   Subcooled or Superheated specific heat capacity ( $\text{J}.\text{kg}^{-1}.\text{K}^{-1}$ ).
C  UF -    Saturated liquid viscosity ( $\text{kg}.\text{m}^{-1}.\text{s}^{-1}$ ).
C  UG -    Saturated vapour viscosity ( $\text{kg}.\text{m}^{-1}.\text{s}^{-1}$ ).
C  UL -    Subcooled or superheated viscosity ( $\text{kg}.\text{m}^{-1}.\text{s}^{-1}$ ).
C  AKF -   Saturated liquid thermal conductivity ( $\text{W}.\text{m}^{-1}.\text{K}^{-1}$ ).
C  AKG -   Saturated vapour thermal conductivity ( $\text{W}.\text{m}^{-1}.\text{K}^{-1}$ ).
C  AKL -   Subcooled or superheated thermal conductivity ( $\text{W}.\text{m}^{-1}.\text{K}^{-1}$ ).
C  PRF -   Saturated liquid Prandtl number.
C  PRG -   Saturated vapour Prandtl number.
C  PRL -   Subcooled or superheated Prandtl number.
C  HFG -   Latent heat of vaporization.
C  SIGMA - Surface tension on gas-liquid interface ( $\text{N}.\text{m}^{-1}$ ).
C
C*****
C
C  COMMON /PROP/VF,VG,VL,RHOF,RHOG,RHOL,HF,HG,HL,CPF,CPG,CPL,
C  $      UF,UG,UL,AKF,AKG,AKL,PRF,PRG,PRL,HFG,SIGMA
C
C*****
C
C  CONST, PARAM --- Internal Common block in which working
C                   variables are being transfered to and from the
C                   internally defined functions.
C*****
C
C  COMMON /CONST/R,B,AA,ALPHA
C  COMMON /PARAM/TR,PR,DEPREF,HFGREF

```

```

C
C*****
C
C   Initializes all constant values.
C
C*****
C
C   R = 8314.
C   B(1)=0.08974-0.03452*W+0.00330*W**2
C   B(2)=0.03686+0.00405*W-0.01073*W**2+0.00157*W**3
C   B(3)=0.15400+0.14122*W-0.00272*W**2-0.00484*W**3
C   AA=0.44869+0.04024*W+0.01111*W**2-0.00576*W**3
C   ALPHA=0.4070+1.3787*W-0.2933*W**2
C
C*****
C
C   Determine the reference state enthalpy departure function
C   necessary for relative enthalpy evaluation.
C
C*****
C
C   TR = TREF/TC
C   PREF=PC*PRSAT(TR,W)
C   VV=VVAP(TREF,PREF)
C   VL=VLIQ(TREF,PREF)
C   ZV=PREF*VV/(R*TREF)
C   ZL=PREF*VL/(R*TREF)
C   HFGREF=ENIFG(TR,ZV,ZL)
C   PR = PRSAT(TR,W)
C   DEFPREF = DEFPENT(TR,PR,ZV)
C       TR = T/TC
C       PR = P/PC
C
C*****
C
C   When saturation state is pre-determined, either the
C   temperature or the pressure in the calling program can
C   be assigned a negative value. This will permit PROPER
C   to call the Saturation subroutine directly.
C
C*****
C
C   IF (T.LT.0.001.OR.P.LT.0.) THEN
C       CALL SATURA(P,T)
C       RETURN
C   ELSE
C       IF (TR.LE.1.0) THEN
C           PSAT=PC*PRSAT(TR,W)
C       ELSE
C           CALL SUPER(P,T)
C       RETURN
C   ENDF

```



```

C
C*****
C
C   If the given pressure is within 0.5% of the saturation
C   pressure calculated from Lee-Kesler equation, then the
C   given condition is assumed to be in saturation.
C
C*****
C
      IF (ABS((P-PSAT)/PSAT).LE.0.005) THEN
        CALL SATURA(P,T)
        RETURN
      ELSE
C
C*****
C
C   Check for superheated or subcooled state.
C
C*****
C
      IF (P.LT.PSAT) THEN
        CALL SUPER(P,T)
        RETURN
      ELSE
        CALL SUBCOOL(P,T)
        RETURN
      ENDIF
    ENDIF
  ENDIF
END

```

```

C
C*****
C
C      Superheated Subroutine
C
C*****
C
SUBROUTINE SUPER(P,T)
  REAL MW,MW1,MW2
  DIMENSION B(3)
  COMMON /CRIT/TC,PC,VC,W,MW,CO1,CO2,CO3,CO4,BO,TO,TREF
  COMMON /PROP/VF,VG,VL,RHOF,RHOG,RHOL,HF,HG,HL,CPF,CPG,CPL,
$      UF,UG,UL,AKF,AKG,AKL,PRF,PRG,PRL,HFG,SIGMA
  COMMON /CONST/R,B,AA,ALPHA
  COMMON /PARAM/TR,PR,DEPREF,HFGREF
  V = VVAP(T,P)
  ZL = P*V/(R*T)
  VL = V/MW
  RHOL=1/VL
  VR = VL/VC
C
C*****
C
C      Enthalpy is calculated relative to the reference state.
C      I.e., the saturated liquid enthalpy at reference temperature
C      was assumed to be zero.
C
C*****
C
      DEP1 = DEPEND(T,PR,ZL)
      HL = ((CPO(T)-CPO(TREF))*4186.8+(R*TC*(DEP1-DEPREF)))
$      /MW + HFGREF
      CPL=CP(T,V)
      UL = VISVAP(T,PR,VR)
      AKL=AKVAP(T,PR,VR)
      PRL=UL*CPL/AKL
RETURN
END

```

```

C
C*****
C
C   Subcooled Subroutine
C
C*****
C
SUBROUTINE SUBCOOL(P,T)
  REAL MW,MW1,MW2
  DIMENSION B(3)
  COMMON /CRIT/TC,PC,VC,W,MW,CO1,CO2,CO3,CO4,BO,TO,TREF
  COMMON /PROP/VF,VG,VL,RHOF,RHOG,RHOL,HF,HG,HL,CPF,CPG,CPL,
$      UF,UG,UL,AKF,AKG,AKL,PRF,PRG,PRL,HFG,SIGMA
  COMMON /CONST/R,B,AA,ALPHA
  COMMON /PARAM/TR,PR,DEFPREF,HFGREF

C
  V = VLIQ(T,P)
  ZL = P*V/(R*T)
  VL = V/MW
  RHOL=1/VL
  DEP = DEPEND(TR,PR,ZL)
  HL = ((CPO(T)-CPO(TREF))*4186.8+(R*TC*(DEP-DEFPREF)))
$      /MW + HFGREF
  CPL = CP(T,P)
  UL = VISLIQ(T)
  AKL = AKLIQ(T,PR,VR)
  PRL = UL*CPL/AKL

RETURN
END

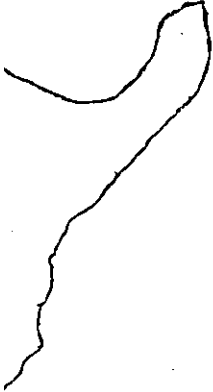
```

```

C
C*****
C
C   Saturation Subroutine
C
C*****
C
SUBROUTINE SATURA(P,T)
  REAL MW,MW1,MW2
  DIMENSION B(3)
  COMMON /CRIT/TC,PC,VC,W,MW,CO1,CO2,CO3,CO4,BO,TO,TREF
  COMMON /PROP/VF,VG,VL,RHOF,RHOG,RHOL,HF,HG,HL,CPF,CPG,CPL,
$      UF,UG,UL,AKF,AKG,AKL,PRF,PRG,PRL,HFG,SIGMA
  COMMON /CONST/R,B,AA,ALPHA
  COMMON /PARAM/TR,PR,DEPREF,HFGREF

  IF(T.LT.0.001). THEN
    TSAT=TC*TRSAT(PR,W)
    T=TSAT
  ELSE
    PSAT=PC*PRSAT(TR,W)
    P=PSAT
    TSAT=T
  ENDIF
  TR = TSAT/TC
  VF1= VLIQ(TSAT,P)
  VG1= WAP(TSAT,P)
  ZF = P*VF1/(R*TSAT)
  ZG = P*VG1/(R*TSAT)
  DEPG = DEPEND(T,PR,ZG)
  VF = VF1/MW
  VG = VG1/MW
  RHOF=1/VF
  RHOG=1/VG
  VRF=VF/VC
  VRG=VG/VC
  HG = ((CPO(TSAT)-CPO(TREF))*4186.8+(R*TC*(DEPG-DEPREF)))/MW
$      + HFGREF
  HFG = ENIFG(TR,ZG,ZF)
  IF(ABS(TSAT-TREF).LT.0.05) THEN
    HF = 0.0
  ELSE
    HF = HG - HFG
  ENDIF
  CPF = CP(TSAT,VF1)
  CPG = CP(TSAT,VG1)
  UF=VISLIQ(T)
  UG=VISVAP(TR,PR,VRG)
  AKF = AKLIQ(T,PR,VR)
  AKG = AKVAP(T,PR,VRG)
  SIGMA = SIG(TR,TC,PC,W)

```



PRF = UF*CPF/AKF
PRG = UG*CPG/AKG
RETURN
END

```

C
C*****
C
C   Function for evaluating vapour molar volume given T and P.
C   Newton-Raphson iteration technique is used.
C
C*****
C
C   FUNCTION VVAP(T,P)
C   REAL COUNT,MW
C   DIMENSION B(3),BB(3)
C   COMMON /CRIT/TC,PC,VC,W,MW,CO1,CO2,CO3,CO4,B0,TO,TREF
C   COMMON /CONST/R,EB,AA,ALPHA
C   TR=T/TC
C   DO 10 I=1,3
C       B(I)=BB(I)*R*TC/PC
10  CONTINUE
C   A=AA*R**2*TC**2*((1+ALPHA*(1-SQRT(TR)))**2)/PC
C
C*****
C
C   Ideal gas volume is used as the initial guess
C
C*****
C
C   VOLD=R*T/P
C   COUNT=1
C
C
C*****
C
C   If there is no convergence within 100 iteration, a message
C   will be prompted to the user.
C
C*****
C
1  IF(COUNT.GT.100) GO TO 3
C   TERM1=P*(VOLD-B(1))*(VOLD-B(2))*(VOLD+B(3)) -R*T*(VOLD-B(2))*
C   $      (VOLD+B(3)) + A*(VOLD-B(1))
C   TERM2=P*((VOLD-B(2))*(VOLD+B(3))+(VOLD-B(1))*(VOLD+B(3))
C   $      +(VOLD-B(1))*(VOLD-B(2))) -R*T*((VOLD-B(2))+(VOLD+B(3)))
C   $      +A
C   VNEW=VOLD-TERM1/TERM2
C   IF(ABS(VNEW-VOLD).LE.0.00010) GO TO 2
C       VOLD=VNEW
C       COUNT=COUNT+1
C   GO TO 1
2  VVAP=VNEW
C   RETURN

```

```

3  VVAR=VNEW
   WRITE(*,11)
11  FORMAT(' NO CONVERGENCE WITHIN 100 ITERATIONS')
   RETURN
   END

```

```

C
C*****
C
C  Function for evaluating liquid molar volume given P and T.
C  Newton-Raphson iteration technique is used.
C
C*****
C
C  FUNCTION VLIQ(T,P)
C  REAL COUNT,MW
C  DIMENSION B(3),BB(3)
C  COMMON /CONST/R,BB,AA,ALPHA
C  COMMON /PROP1/TC,PC,VC,W,MW,CO1,CO2,CO3,CO4,BO,TO,TREF
C  TR=T/TC
C  DO 10 I=1,3
C     B(I)=BB(I)*R*TC/PC
10  CONTINUE
C     A=AA*R**2*TC**2*((1+ALPHA*(1-SQRT(TR)))**2)/PC
C
C*****
C
C  A very small value is used as the initial guess to ensure
C  it will converge to the smallest root.
C
C*****
C
C  VOLD=0.001
C  COUNT=1
C
C*****
C
C  If there is no convergence within 100 iteration, a message
C  will be prompted to the user.
C
C*****
C
1  IF(COUNT.GT.100) GO TO 3
   TERM1=P*(VOLD-B(1))*(VOLD-B(2))*(VOLD+B(3)) -R*T*(VOLD-B(2))*
$      (VOLD+B(3)) + A*(VOLD-B(1))
   TERM2=P*((VOLD-B(2))*(VOLD+B(3)) + (VOLD-B(1))*(VOLD+B(3)) +
$      (VOLD-B(1))*(VOLD-B(2))) - R*T*((VOLD-B(2)) +
$      (VOLD+B(3))) + A

```

```

VNEW=VOLD-TERM1/TERM2
IF ( (ABS (VNEW-VOLD)/VOLD) .LE.0.0001) GO TO 2
  VOLD=VNEW
  COUNT=COUNT+1
GO TO 1
2  VLIQ=VNEW
RETURN
3  VLIQ=VNEW
WRITE(*,11)
11' FORMAT(' NO CONVERGENCE WITHIN 100 ITERATIONS')
RETURN
END

```

```

C
C*****
C
C  Function for evaluating enthalpy departure function.
C
C*****
C

```

```

  FUNCTION DEPENT(TR,PR,Z)
  DIMENSION B(3)
  COMMON /CONST/R,B,AA,ALPHA
  TERM1=(Z-1)*TR
  TERM2=AA*ALPHA*(1+ALPHA*(1-SQRT(TR)))*SQRT(TR)
  TERM3=AA*(1+ALPHA*(1-SQRT(TR)))**2
  TERM4=LOG(ABS((Z-B(2)*PR/TR)/(Z+B(3)*PR/TR)))
  DEPENT = TERM1+((TERM2+TERM3)*TERM4)/(B(2)+B(3))
  RETURN
END

```

```

C
C*****
C
C  Function for evaluating Latent Heat of Vaporization using
C  Clapeyron relation.
C
C*****
C

```

```

  FUNCTION ENIFG(TR,ZV,ZL)
  COMMON /PROP1/TC,PC,VC,W,MW,CO1,CO2,CO3,CO4,BO,TO,TREF
  REAL MW
  R = 8314.
  PSI = 6.09648 - 1.28862*TR + 1.016082*TR**7
  $      + W*(15.6875 - 13.4721*TR + 2.61462*TR**7)
  ENIFG = PSI*R*TC*(ZV-ZL)/MW
  RETURN
END

```



```

C
C*****
C
C   Lee-Kesler equation for saturation pressure evaluation.
C.
C*****
C
C   FUNCTION PRSAT (TR,W)
C   TERM = 5.92714 - 6.09648/TR - 1.28862*LOG(TR) + 0.169347*TR**6
C   $      + W*(15.2518 - 15.6875/TR -13.4721*LOG(TR)+0.43577*TR**6)
C   PRSAT = EXP(TERM)
C   RETURN
C   END

C
C*****
C
C   Determination of saturation temperature by iteration method
C   through the use of Lee-Kesler equation.
C
C*****
C
C   FUNCTION TRSAT(PR,W)
C   TR = 0.5
C   COUNT = 1.
C   N = 100

C
C*****
C
C   If there is no convergence within 100 iteration, a message
C   will be prompted to the user.
C
C*****
C
C   1 IF(COUNT.GT.N) GO TO 3
C     TERM1 = LOG(PR)-5.92714+6.09648/TR+1.28862*LOG(TR)-0.169347*
C   $      TR**6 -W*(15.2518-15.6875/TR-13.4721*LOG(TR)+0.43577*TR**6)
C     TERM2 = -6.09648/TR**2 + 1.28862/TR - 1.016082*TR**5 -
C   $      W*(15.6875/TR**2 - 13.4721/TR + 2.61462*TR**5)
C     TRNEW = TR - TERM1/TERM2
C     IF (ABS(TRNEW-TR).LE.0.001) GO TO 2
C       TR = TRNEW
C       COUNT = COUNT + 1.
C       GO TO 1
C   2   TRSAT = TRNEW
C       RETURN
C   3   TRSAT = TRNEW
C       WRITE(*,10) N
C   10  FORMAT(/,T2,'NO CONVERGENCE WITHIN',I4,' ITERATIONS')
C       RETURN
C       END

```

```

C
C*****
C
C   Integral of ideal gas specific heat capacity
C
C*****
C

```

```

      FUNCTION CPO(T)
      COMMON /PROP1/TC,PC,VC,W,MW,A,B,C,D,BO,TO,TREF
      CPO = T*(A+T*(B/2+T*(C/3+D*T/4)))
      RETURN
      END

```

```

C
C*****
C
C   Function for evaluating viscosity of gases.
C
C*****
C

```

```

      FUNCTION VISVAP(TR,PR,VR)
      REAL MW
      COMMON /PROP1/TC,PC,VC,W,MW,CO1,CO2,CO3,CO4,BO,TO,TREF
      PCA = PC/101325.
      DENSE = 0.1875*TR - 0.125
      ZETA = TC**0.16667/(SQRT(MW)*PCA**0.66667)
      VISG=(4.610*TR**0.618-2.04*EXP(-0.449*TR)
$      + 1.94*EXP(-4.058*TR) + 0.1)/ZETA

```

```

C
C*****
C
C   The low density gas viscosity is assumed first using the method
C   of Thodos et al. If the gas is at high density, Jossi et al.
C   equation is used.
C
C*****
C

```

```

      IF (PR.GE.DENSE) THEN
      RHS = 1.0230 + 0.23364/VR + 0.58533/VR**2
$      - 0.40758/VR**3 + 0.093324/VR**4
      VISG=VISG + (RHS**4 - 1)/ZETA
      ENDIF
      VISVAP = VISG*1.0E-7
      RETURN
      END

```

```

C
C*****
C
C   Function for Evaluating liquid viscosity.
C
C*****
C
C   FUNCTION VISLIQ(T)
C   REAL MW
C   COMMON /PROP1/TC,PC,VC,W,MW,CO1,CO2,CO3,CO4,BO,TO,TREF
C   PCA = PC/101300.
C   TR = T/TC
C
C*****
C
C   Van Velzen et al.'s equation is used for low temperature
C   liquid viscosity and Letsou and Stiel's equation is used
C   for high temperature liquid viscosity calculation.
C
C*****
C
C   IF (TR.GE.0.75) THEN
C       TERM1 = 0.015174 - 0.02135*TR + 0.0075*TR**2
C       TERM2 = 0.042552 - 0.07674*TR + 0.0340*TR**2
C       ZETA = TC**0.16667/(SQRT(MW)*PCA**0.66667)
C       VISLIQ = ((TERM1 + W*TERM2)/ZETA)/1000.
C   ELSE
C       VISLIQ = (EXP(BO*(1/T - 1/TO)))/1000.
C   ENDIF
C   RETURN
C   END

C
C*****
C
C   Function for evaluating specific heat capacity. Equation was
C   derived from the equation of state suggested by Adachi et al.
C
C*****
C
C   FUNCTION CP(T,V)
C   REAL MW
C   DIMENSION BI(3),B(3)
C   COMMON /PROP1/TC,PC,VC,W,MW,CO1,CO2,CO3,CO4,BO,TO,TREF
C   COMMON /CONST/R,B,AA,ALPHA
C   TR=T/TC
C   DO 10 I=1,3
C       BI(I) = B(I)*R*TC/PC
C 10 CONTINUE

```

```

      A = AA*R**2*TC**2/PC
      AT=A*(1+ALPHA*(1-SQRT(TR))**2
      DADT=A*ALPHA*((1+ALPHA)/SQRT(TR) - ALPHA)/TC
      D2ADT2=A*ALPHA*(1+ALPHA)*TR**(-1.5)/(2*TC**2)
      DPDIV=R/(V-BI(1)) -DADT/((V-BI(2))*(V+BI(3)))
      DPDVT=R*T/(V-BI(1))**2 + AT*(1/(V-BI(2))**2 -1/(V+
$      BI(3))**2)/(BI(2)+BI(3))
      CPG1=(-T*D2ADT2*LOG((V-BI(2))/(V+BI(3)))/(BI(2)+BI(3))
$      -DPDIV*(R*T/(V-BI(1))-T*DADT/((V-BI(2))*(V+BI(3))))
$      /DPDVT -R)+(CO1+T*(CO2+T*(CO3+T*CO4)))*4186.8
      CP=CPG1/MW
      RETURN
      END

```

```

C
C*****
C
C      Function for evaluating thermal conductivity of gases.
C
C*****
C
      FUNCTION AKVAP(T,PR,VR)
      REAL MW,LAMDAO
      COMMON /PROP1/TC,PC,VC,W,MW,CO1,CO2,CO3,CO4,BO,TO,TREF
      TR=T/TC
      PCA = PC/101300.
      RHOR=1/VR
      ZC = PC*VC*MW/(TC*8314)
      ZETA=TC**0.16667/(SQRT(MW)*PCA**0.66667)
      VISO=(4.610*TR**0.618-2.04*EXP(-0.449*TR)+1.94*EXP(-4.058*TR)
$      + 0.1)/ZETA/1000000.
      CV = CO1+T*(CO2+T*(CO3+T*CO4)) - 1.98
      LAMDAO=VISO*(1.16*CV+4.00)/MW
      DENSE = 0.1875*TR - 0.125
C
C*****
C
C      Stiel and Thodos's equations are used for both the low and
C      high density gases.
C
C*****
C
      IF(PR.LE.DENSE) THEN
        AKVAP=LAMDAO
      ELSE
        TAL = ZETA*MW
        CONSTANT=TAL*ZC**5

```

```

IF(RHOR.LT.0.5) THEN
  AKVAP=(14.0E-8*(EXP(0.535*RHOR)-1)/CONSTANT)+LAMDAO
ELSE
  IF(RHOR.LT.2.0) THEN
    AKVAP=(13.1E-8*(EXP(0.67*RHOR)-1.069)/CONSTANT)+LAMDAO
  ELSE
    AKVAP=(2.976E-8*(EXP(1.155*RHOR)+2.016)/CONSTANT)+LAMDAO
  ENDIF
ENDIF
ENDIF
AKVAP=418.68*AKVAP
RETURN
END

```

```

C
C*****
C
C  Function for evaluating liquid thermal conductivity. The
C  Sato-Riedel's method is employed.
C
C*****
C
  FUNCTION AKLIQ(T,PR,VR)
  COMMON /PROP1/TC,PC,VC,W,MW,CO1,CO2,CO3,CO4,BO,TO,TREF
  REAL MW
  TR=T/TC
  IF(TR.LT.0.3) THEN
    PRB = 101300./PC
    TRB = TRSAT(PRB,W)
    AKL = 2.64E-3*(3+20*(1-TR)**0.66667)/(3+20*(1-TRB)**0.66667)
    AKLIQ = 418.68*AKL/SQRT(MW)
  ELSE
    AKLIQ = AKVAP(T,PR,VR)
  ENDIF
  RETURN
  END

```

```

C
C*****
C
C  Function for evaluating surface tension using Brock and Brock's
C  approach.
C*****
C
FUNCTION SIG(TR,TC,PC,W)
  PER = (101300/PC)
  TER = TRSAT(PER,W)
  THETA=0.1207*(1+TER*LOG(PC/101300)/(1-TER)) - 0.281
  SIG =(PC/101300)**0.66667*TC**0.3333*THETA*(1-TR)**(11./9.)/1000.
  RETURN
END

```

Appendix C

PROCEDURE FOR PREDICTING HORIZONTAL FLOW CHF

C.1 Input Parameters

The input parameters required for the prediction are the pressure in kPa , mass flux in $kg.m^{-2}.s^{-1}$, thermodynamic vapour quality and the tube diameter in m . With these given flow conditions, fluid properties and the parameter T_1 will be calculated. The CHF ratio can then be predicted based on the local parameters approach or the constant inlet condition approach.

C.2 Calculation Procedure

C.2.1 Evaluation of Fluid Properties

The saturation properties of the fluid are estimated from the UOCODE (for water) and from non-aqueous property code, PROPER (for fluids other than water). The list of constants shown in Table B-4 for the fluid of interest must be given before the properties can be calculated. These critical constants are passed to the property sub-

routine through a common block called CRIT. The estimated properties will be passed back to the calling program through a common block called PROP. An example of the calling process is shown in figure C1. The program calculates the fluid properties of freon-12 and print out the values for saturated liquid specific volume (VF), saturated vapour specific volume (VG) and the single phase specific volume (VL). For this case, the fluid is in the superheated vapour state and thus VL corresponds to the superheated vapour specific volume. Consequently, subroutine PROPER only calculate the superheated volume and assign zero values to the saturated properties. The source code for property subroutine can be found in Appendix B.

C.2.2 Evaluation of Actual Quality

When analyzing the force balance, actual void fraction and quality are needed. The method suggested by Saha and Zuber (1974) was used for actual quality evaluation (see Chapter 4). Heat flux, tube diameter and fluid properties are required for the intermediate calculation steps. Normally, the heat flux is not known if only the local parameters are given. Critical heat flux for vertical flow is used as the estimate of the heat flux. The predicted actual quality is then used to predict CHF ratio which in turn yield the value for horizontal CHF. The flowchart for actual quality evaluation subroutine is shown in figure C2. For thermodynamic qualities greater than 20%, the actual quality can be assumed equal to the thermodynamic quality.

C.2.3 Evaluation of Void Fraction

CISE (1970) equation is chosen for the slip ratio estimation and subsequently the void fraction is evaluated from the relation

$$\alpha = \frac{X}{X + S(1 - X)} \quad (C.1)$$

where S is the slip ratio calculated from equation (4.33) and X is the actual quality.

C.2.4 Evaluation of Parameter T_1

With the fluid properties, actual quality and void fraction, equation (5.22) is used to calculate the value of parameter T_1 with $C_1 = 1.0$. Re_L is defined as $G(1-X)D/\mu_f$ in equation (5.22). T_1 is then substituted into equation (6.9) for the evaluation of CHF ratio.

C.3 CHF Ratio Prediction Based on Local Parameter Approach

The CHF ratio ($CHFR$) is evaluated by the use of equation (6.9), i.e.;

$$CHFR = 1 - e^{-(T_1/65)^{0.5}} \quad (C.2)$$

Horizontal CHF values can then be obtained from

$$CHF_{hor} = CHFR \times CHF_{ver} \quad (C.3)$$

where value for CHF_{ver} can be taken from Table 1.

C.4 CHF Ratio Prediction Based on Constant Inlet Condition Approach

For this method, the inlet subcooling and the heated length must be known. The exit quality is varied until the heat flux calculated from energy balance is the same as the critical heat flux predicted based on that local exit quality (see figure 41a).

C.5 User Friendly Tabular Method

Despite the correct trend of equation (6.9) with the mass flux, it would under-predict the CHF ratio considerably for certain flow conditions (high pressure and moderate

mass flux). The reason is that the exponential function would not converge to the value of 1.0 soon enough even though the mass flux value is supposed to be high enough to suppress gravity effect. A simple correction for this deficiency is to take the maximum value of $CHFR$ calculated from both equation (6.9) and equation (2.25). Figure C3 shows the prediction of CHF ratio by the two methods mentioned. For mass flux greater than G_A , equation (2.25) predicts a higher value of $CHFR$. If equation (2.25) is used for mass flux greater than G_A , the prediction will converge to the value of 1.0 sooner.

This combined approach was used to produce a CHF ratio ($CHFR$) table for water (see Table C-1). The $CHFR$ table provides users with an easy and quick way of estimating the CHF ratio. Table C-1 is only valid for an 8mm inner diameter tube. The CHF ratio is found to decrease with increasing tube diameter as illustrated by figure 37. Tube diameter correction factor for CHFR is approximated by

$$K_{dia} = \left(\frac{0.008}{D} \right)^{0.3} \quad (C.4)$$

for $0.005m \leq D \leq 0.016m$ and tube diameter correction factor for vertical CHF is given by

$$K_1 = \left(\frac{0.008}{D} \right)^{0.33} \quad (C.5)$$

Therefore, horizontal CHF can be calculated as

$$CHF_{hor} = K_{dia} \times K_1 \times CHFR_{8mm} \times CHF_{ver,8mm} \quad (C.6)$$

$$CHF_{hor} = (0.008/D)^{0.63} \times CHFR_{8mm} \times CHF_{ver,8mm} \quad (C.7)$$

where $CHFR_{8mm}$ is the $CHFR$ value taken from Table C-1 and $CHF_{ver,8mm}$ is the corresponding vertical CHF value taken from Table 1 (under the same G , X and P). Table C-1 was arranged in a matrix form so that simple linear interpolation is possible. The $CHFR$ values are tabulated against thermodynamic quality so that no further calculation for actual quality is needed. Values with asterisks are extrapolated from the higher qualities region. They correspond to the conditions where the actual qualities are equal to zero. Table C-1 was used to predict CHF ratio and compared to

the data bank. The results for water and freon-12 comparison are summarized in Table C-2. It is clear that similar type of error distribution is found by using Table C-1 as compared to the step-by-step calculations outlined earlier. It is therefore worthwhile to lose some accuracy when the prediction method is so simple to apply such as the tabular approach.

C.6 Source Code for Horizontal CHF Prediction

The prediction subroutine can be divided into three levels. Level one is the main subroutine where the input parameters are read in. It is in this level that the necessary subroutines are called and the main calculations are being performed. Figure C4 shows schematically the flow of information in level one.

Level two is the main backbone of the whole program. It calls the other subroutines in level three needed for intermediate calculations. Property subroutines is being called first and subsequently subroutines such as XACT and VOID are called so that T_1 can be evaluated. The flowchart for CHFRAT in second Level is shown in figure C5. CHFRAT is the subroutine which calculates the CHF ratio.

Subroutines in level three are PROPER, XACT and VOID. The source code for the whole prediction program is listed in figure C6.

Table C-1. CHF Ratio ($\text{CHF}_{\text{hor}}/\text{CHF}_{\text{ver}}$) Table for Water

		D = 8.0 mm																		D = 8.0 mm															
		G (kg/m.s)		QUALITY																G (kg/m.s)		QUALITY													
		-0.15	-0.10	-0.05	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.70	0.80	0.90															
100	50	0.00	0.00	0.00	0.000	0.000	0.076	0.088	0.098	0.105	0.112	0.117	0.122	0.125	0.128	0.131	0.132	0.134	0.135	0.135															
100	100	0.04	0.04	0.04	0.044	0.117	0.153	0.179	0.200	0.218	0.233	0.247	0.259	0.271	0.281	0.291	0.300	0.319	0.338	0.364															
100	200	0.11	0.11	0.11	0.105	0.234	0.305	0.358	0.402	0.441	0.476	0.507	0.537	0.564	0.590	0.615	0.638	0.664	0.730	0.781															
100	300	0.19	0.19	0.19	0.191	0.355	0.451	0.523	0.585	0.637	0.683	0.722	0.757	0.788	0.815	0.840	0.862	0.899	0.930	0.959															
100	400	0.29	0.29	0.29	0.293	0.478	0.589	0.669	0.735	0.787	0.830	0.865	0.893	0.915	0.934	0.949	0.960	1.000	1.000	1.000															
100	500	0.41	0.41	0.41	0.413	0.600	0.712	0.788	0.848	0.887	0.920	0.943	0.960	0.981	1.000	1.000	1.000	1.000	1.000	1.000															
100	700	0.54	0.54	0.54	0.543	0.726	0.828	0.895	0.935	0.962	0.985	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000															
100	1000	0.83	0.830	0.890	0.901	0.937	0.985	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000															
100	1500	0.975	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000															
100	2000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000															
100	2500	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000															
100	3000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000															
100	3500	1.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000															
200	50	0.00	0.00	0.00	0.000	0.000	0.000	0.076	0.084	0.090	0.096	0.100	0.103	0.105	0.107	0.108	0.109	0.108	0.105	0.099															
200	100	0.04	0.04	0.04	0.042	0.102	0.132	0.153	0.170	0.184	0.196	0.204	0.214	0.221	0.228	0.233	0.238	0.246	0.253	0.261															
200	200	0.09	0.09	0.09	0.092	0.200	0.259	0.302	0.337	0.367	0.393	0.416	0.437	0.457	0.475	0.493	0.510	0.544	0.579	0.623															
200	300	0.16	0.16	0.16	0.157	0.297	0.378	0.440	0.490	0.531	0.570	0.604	0.634	0.662	0.688	0.713	0.735	0.778	0.819	0.864															
200	400	0.23	0.23	0.23	0.232	0.393	0.489	0.563	0.623	0.673	0.716	0.752	0.785	0.813	0.838	0.860	0.879	0.913	0.941	0.966															
200	500	0.31	0.31	0.31	0.309	0.488	0.590	0.671	0.733	0.784	0.824	0.858	0.885	0.907	0.926	0.941	0.953	0.972	0.992	0.994															
200	700	0.48	0.48	0.48	0.480	0.652	0.755	0.830	0.882	0.919	0.945	0.963	0.980	1.000	1.000	1.000	1.000	1.000	1.000	1.000															
200	1000	0.55	0.55	0.55	0.561	0.701	0.831	0.905	0.951	0.974	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000															
200	1500	0.69	0.69	0.69	0.689	0.888	0.960	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000															
200	2000	0.78	0.78	0.78	0.713	0.943	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000															
200	2500	0.88	0.88	0.88	0.879	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000															
200	3000	1.00	1.00	1.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000															
200	3500	1.00	1.00	1.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000															
500	50	0.00	0.00	0.00	0.000	0.000	0.000	0.000	0.369	0.074	0.078	0.081	0.084	0.085	0.087	0.087	0.087	0.085	0.079	0.070															
500	100	0.04	0.04	0.04	0.039	0.083	0.108	0.123	0.139	0.149	0.158	0.165	0.171	0.175	0.179	0.183	0.183	0.183	0.180	0.174															
500	200	0.08	0.08	0.08	0.079	0.163	0.210	0.244	0.271	0.293	0.312	0.328	0.341	0.354	0.364	0.374	0.383	0.399	0.414	0.434															
500	300	0.13	0.13	0.13	0.125	0.239	0.305	0.354	0.392	0.425	0.452	0.477	0.499	0.519	0.537	0.554	0.571	0.602	0.634	0.675															
500	400	0.18	0.18	0.18	0.176	0.314	0.394	0.454	0.502	0.542	0.577	0.607	0.635	0.660	0.683	0.704	0.725	0.763	0.800	0.843															
500	500	0.23	0.23	0.23	0.232	0.386	0.477	0.544	0.599	0.644	0.682	0.716	0.746	0.772	0.796	0.817	0.837	0.872	0.904	0.937															
500	700	0.34	0.34	0.34	0.358	0.519	0.620	0.695	0.753	0.799	0.836	0.867	0.892	0.912	0.929	0.943	0.955	0.973	0.985	0.995															
500	1000	0.54	0.54	0.54	0.539	0.686	0.783	0.847	0.895	0.928	0.951	0.969	0.980	1.000	1.000	1.000	1.000	1.000	1.000	1.000															
500	1500	0.60	0.60	0.60	0.533	0.729	0.859	0.926	0.977	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000															
500	2000	0.70	0.70	0.70	0.698	0.820	0.937	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000															
500	2500	0.87	0.87	0.87	0.870	0.969	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000															
500	3000	1.00	1.00	1.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000															
500	3500	1.00	1.00	1.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000															
1000	50	0.00	0.00	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.070	0.072	0.073	0.074	0.074	0.074	0.072	0.066	0.057															
1000	100	0.04	0.04	0.04	0.040	0.071	0.092	0.106	0.118	0.127	0.134	0.140	0.145	0.149	0.151	0.153	0.153	0.151	0.145	0.134															
1000	200	0.09	0.09	0.09	0.085	0.142	0.179	0.207	0.230	0.248	0.263	0.276	0.284	0.295	0.303	0.309	0.314	0.321	0.324	0.328															
1000	300	0.14	0.14	0.14	0.144	0.218	0.264	0.302	0.331	0.359	0.382	0.401	0.418	0.433	0.444	0.454	0.468	0.488	0.507	0.532															
1000	400	0.21	0.21	0.21	0.208	0.291	0.346	0.392	0.429	0.461	0.489	0.514	0.534	0.556	0.574	0.591	0.606	0.637	0.667	0.706															
1000	500	0.23	0.23	0.23	0.232	0.317	0.374	0.425	0.476	0.518	0.545	0.564	0.589	0.612	0.633	0.653	0.673	0.703	0.737	0.792															
1000	700	0.25	0.25	0.25	0.247	0.344	0.403	0.458	0.503	0.548	0.575	0.594	0.619	0.642	0.663	0.683	0.703	0.731	0.757	0.833															
1000	1000	0.36	0.36	0.36	0.359	0.484	0.601	0.679	0.738	0.788	0.825	0.842	0.867	0.892	0.912	0.929	0.943	0.955	0.973	0.985															
1000	1500	0.52	0.518	0.704	0.792	0.848	0.890	0.925	0.960	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000															
1000	2000	0.70	0.699	0.750	0.856	0.948	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000															
1000	2500	0.88	0.879	0.938	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000															
1000	3000	1.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000																					

4



Table C-2. Comparison of Prediction Accuracy Between The CHF Ratio Table and Equation (6.9)

Prediction Method	Average ⁺ Error	RMS Error	Standard Deviation ⁺	Fraction of data ⁺⁺ within prediction accuracy of		
				±10%	±20%	±30%
<u>Constant X_{DO}</u>						
CHFR Table (Table C-1)	0.005	0.278	0.278	0.1885	0.4577	0.9308
Eq. (6.9)	-0.044	0.259	0.255	0.2654	0.5423	0.9462
<u>Constant X_{IN}</u>						
CHFR Table (Table C-1)	-0.022	0.181	0.181	0.3846	0.7615	1.0000
Eq. (6.9)	-0.029	0.165	0.165	0.3615	0.7462	1.0000

⁺ Mean of $(CHFR_{pred} - CHFR_{expt})/CHFR_{expt}$

⁺⁺ No. of data point = 260.

```

C
C*****
C
C   Example program for estimating fluid properties of Freon-12.
C
C*****
C
  PROGRAM FREON12
  REAL MW
  COMMON /CRIT/TC,PC,VC,W,MW,CO1,CO2,CO3,CO4,BO,TO,TREF
  COMMON /PROP/VF,VG,VL,RHOF,RHOG,RHOL,HF,HG,HL,CPF,CPG,CPL,
  $      UF,UG,UL,AKF,AKG,AKL,PRF,PRG,PRL,HFG,PSAT,TSAT,SIGMA
  TC=369.2
  PC=4973830.
  VC=0.0019056
  W=0.215
  MW=86.469
  CO1=4.132
  CO2=3.865E-2
  CO3=-2.794E-5
  CO4=7.305E-9
  BO=532.855
  TO=156.928
  TREF=233.15
  P = 300000.
  T = 400.
  CALL PROPER(P,T)
  WRITE(*,10) VF,VG,VL,HF,HG,HL,CPF,CPG,CPL,UF,UG,UL,
  $          AKF,AKG,AKL,SIGMA,T,P
10  FORMAT(//,T2,'VF =',E15.5,T25,'VG =',E15.5,T48,'VL =',E15.5,//,
  $          T2,'HF =',E15.5,T25,'HG =',E15.5,T48,'HL =',E15.5,//,
  $          T2,'CPF =',E15.5,T25,'CPG =',E15.5,T48,'CPL =',E15.5,
  $          //,T2,'VISF=',E15.5,T25,'VISG=',E15.5,T48,'VISL=',E15.5,
  $          //,T2,'AKF =',E15.5,T25,'AKG =',E15.5,T48,'AKL =',E15.5,
  $          //,T2,'SIGMA =',E15.5,T25,'T =',E15.5,T45,'P =',E15.5)
  STOP
  END

```


VF =	0.00000E+00	VG =	0.00000E+00	VL =	0.12593E+00
HF =	0.00000E+00	HG =	0.00000E+00	HL =	0.34709E+06
CPF =	0.00000E+00	CPG =	0.00000E+00	CPL =	0.76401E+03
VISF=	0.00000E+00	VISG=	0.00000E+00	VISL=	0.17288E-04
AKF =	0.00000E+00	AKG =	0.00000E+00	AKL =	0.16752E-01
SIGMA =	0.00000E+00	T =	0.40000E+03	P =	0.30000E+06

Figure C1. Example Program listing for Evaluating Fluid Properties.

Subroutine XACT

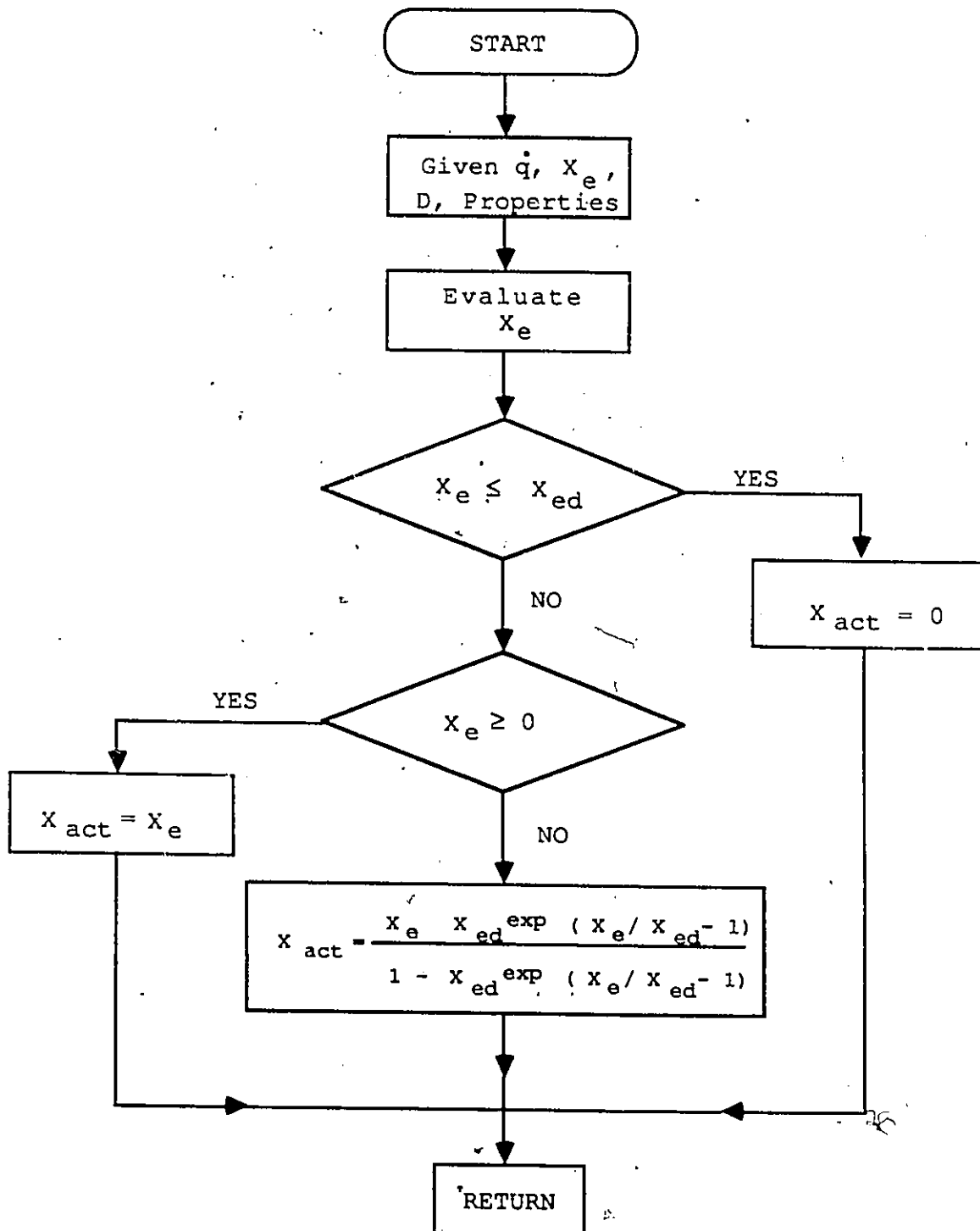


Figure C2. Flowchart for Actual Quality Subroutine.

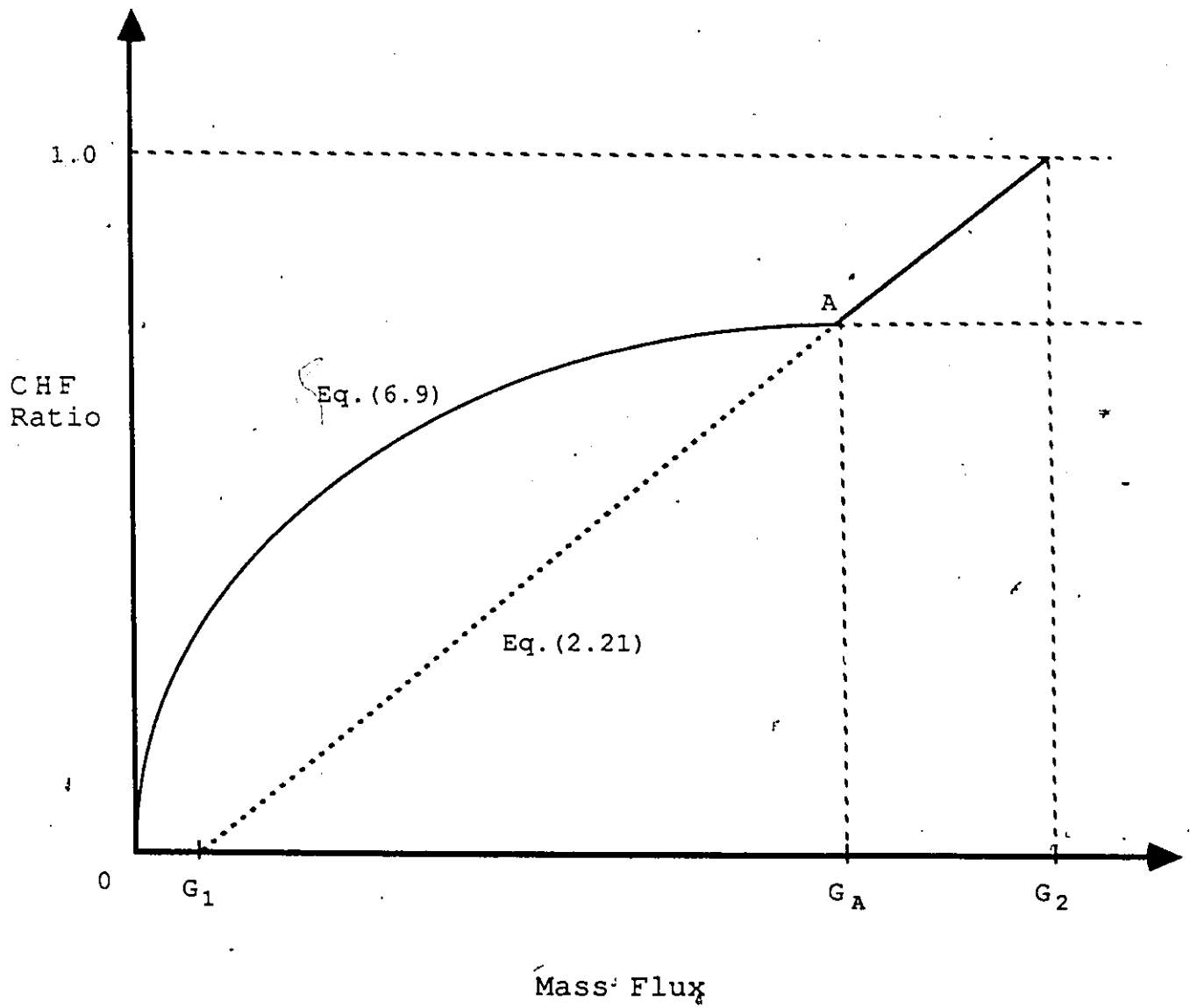


Figure C3. CHF Ratio Prediction as a Function of Mass Flux.

Main Program CHEHOR

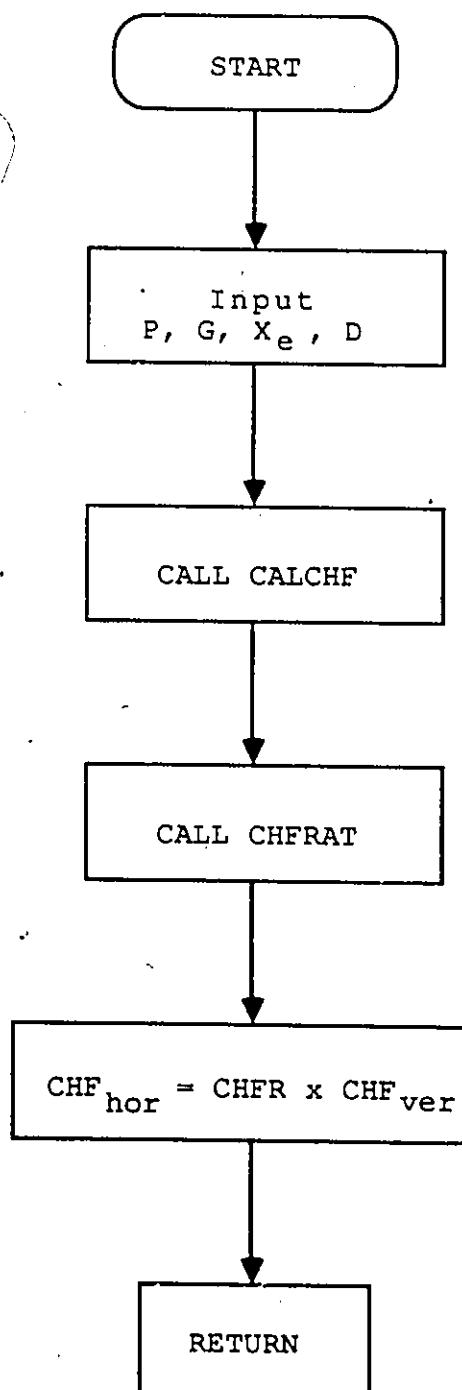


Figure C4. Flowchart for Main Program of Horizontal CHF Prediction.

Subroutine CHERAT

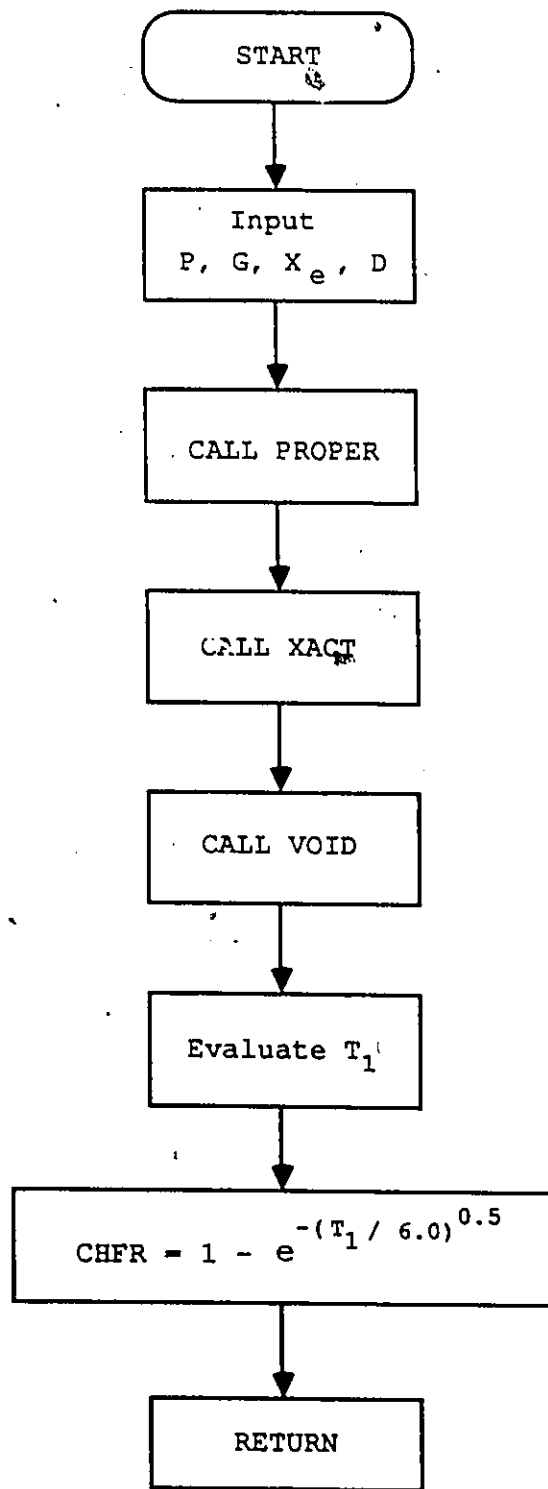


Figure C5. Flowchart for CHF Ratio Subroutine.

```

C
C*****
C
C   Main subroutine for horizontal CHF prediction
C
C*****
C
C   SUBROUTINE CHFHOR(P,G,XE,DHY,CHFH)
C
C*****
C
C   Call subroutine CALCHF to get the CHF value for vertical flow
C
C*****
C
C   CALL CALCHF(P,G,XE,DHY,CHFV)
C
C*****
C
C   Call subroutine CHFRRAT to get the value for CHF ratio
C
C*****
C
C   CALL CHFRRAT(P,G,XE,DHY,CHFR)
C
C*****
C
C   Calculating CHF value for horizontal flow
C
C*****
C
C   CHFH = CHFR*CHFV
C   RETURN
C   END

```

Figure C6. Source Code for CHF Prediction Program

Q

```

C
C*****
C
C      Subroutine to calculate CHF ratio
C      Pressure in KPa
C      Mass flux in kg/m**2/s
C      Diameter in m.
C
C*****
C
C      SUBROUTINE CHFRAI(P,G,XE,DHY,CHFR)
C
C*****
C
C      PROP — Common block in which all the calculated fluid
C      properties are passed to this calling subroutine.
C
C*****
C
C      COMMON/PROP/  VF,  VG,  VL, RHOF, RHOG, RHOL,
+                  HF,  HG,  HL, CPF, CPG, CPL,
+                  VISF, VISG, VISL, AKF, AKG, AKL,
+                  PRF, PRG, PRL, HFG, PSAT, TSAT,
+                  SIGMA
C
C      PSATU = P
C      TSATU = 0.0
C
C
C*****
C
C      Call the property subroutine for evaluating saturation fluid
C      properties at the given pressure.
C
C*****
C
C      CALL PROPER(PSATU,TSATU)
C
C*****
C
C      If the thermodynamic quality is less than 20%, calculate
C      the actual quality using the Saha-Zuber equation, and the
C      vertical CHF as the estimate for heat flux. If it is
C      greater than 20%, assume the actual quality to be the same
C      as the thermodynamic quality.
C
C*****
C
C      IF (XE.LE.0.2) THEN
C      CALL CALCHF (P,G,XE,DHY,CHFVER)
C      QQ = CHFVER*1000.

```

Figure C6. (Cont'd)

```

C
C      CALCULATE ACTUAL QUALITY
C
C          CALL XACT(QQ,G,DHY,XE,X)
C
C      ELSE
C          X = XE
C      ENDIF
C
C*****
C
C      Void fraction is calculated through subroutine VOID using
C      CISE equation.
C*****
C
C          CALL VOID(G,X,DHY,ALPHA)
C
C*****
C
C      Value of the force balance parameter T1 is evaluated and
C      the CHF ratio can thus be calculated
C*****
C
C          REL=G*(1-X)*DHY/VISF
C          TERM1=REL**(-0.2)
C          TERM2=(1-X)/(1-ALPHA)
C          TERM3=G**2/(9.81*DHY*RHO*F*(RHO*F-RHO*G))
C          TT1=0.092*TERM1*TERM2**2*TERM3/SQRT(ALPHA)
C          CHFR=1-EXP(-(TT1/6.0)**0.5)
C      RETURN
C      END

```

Figure C6. (Cont'd)

```

C
C*****
C
C      Subroutine to calculate actual quality
C
C      P in KPa, G in kg.m-2.s-1, DHY in meter and
C      QQ in W.m-2
C*****
C
C      SUBROUTINE XACT(QQ,G,DHY,XE,XA)
C      COMMON/PROP/  VF,  VG,  VL, RHOF, RHOG, RHOL,
+                   HF,  HG,  HL, CPF, CPG, CPL,
+                   VESF, VISG, VISL, AKF, AKG, AKL,
+                   PRF, PRG, PRL, HFG, PSAT, TSAT,
+                   SIGMA
C*****
C
C      Calculate quality at bubble departure, XED
C*****
C
C      PE = G*DHY*CPF/AKF
C      BOIL = QQ/(G*HFG)
C      IF(PE.GT.70000.) THEN
C          XED = -154*BOIL
C      ELSE
C          XED = -0.0022*(PE*BOIL)
C      ENDIF
C
C
C
C      IF(XE.LE.XED) THEN
C          XA = 0.0
C          RETURN
C      ELSE
C          IF(XED.GE.0.) THEN
C              XA = XE
C              RETURN
C          ELSE
C              EXPON=XE/XED
C              IF(EXPON.LE.(-20.0)) EXPON=-20.0
C              EE = XED*EXP(EXPON-1)
C              XA = (XE - EE)/(1-EE)
C          ENDIF
C      ENDIF
C      RETURN
C      END

```

```

C
C*****
C
C      Subroutine for estimating void fraction
C
C      G in kg.m-2.s-1, DHY in m and X is the actual quality
C
C*****
C
C      SUBROUTINE VOID(G,X,DHY,ALPHA)
C
C*****
C      PROP — Common block through which the calculated saturation
C             fluid properties are passed to this subprogram.
C
C*****
C      COMMON/PROP/  VF,  VG,  VL, RHOF, RHOG, RHOL,
+                   HF,  HG,  HL, CPF, CPG, CPL,
+                   VISF, VISG, VISL, AKF, AKG, AKL,
+                   PRF, PRG, PRL, HFG, PSAT, TSAT,
+                   SIGMA
C
C*****
C      Calculation of void fraction using CISE equation.
C
C*****
C
      VR1 = X*RHOF/(RHOG*(1-X))
      RE = G*DHY/VISF
      BETA=RHOF*X/(RHOF*X+RHOG*(1-X))
      WE=G**2*DHY/(SIGMA*RHOF)
      E1=1.578*RE**(-0.19)*(RHOF/RHOG)**0.22
      E2=0.0273*WE*RE**(-0.51)*(RHOF/RHOG)**(-0.08)
      YY=BETA/(1-BETA)
      ARGU = YY/(1+YY*E2)-YY*E2
      IF(ARGU.LE.0.) ARGU=0.0
      SRATIO=1+E1*SQRT(ARGU)
      IF(SRATIO.LT.1.0) SRATIO=1.0
      ALPHA = 1/(1+SRATIO/VR1)
      RETURN
      END

```


SUBROUTINE CALCHF(P,G,D,X,CHF)

```

C*****
C
C      Subroutine CALCHF
C
C      This subroutine is used to obtain the CHF from table of discrete
C      values. The table was presented by Groeneveld et al..
C
C*****

```

```

C*****
C
C      Variable declaration:
C
C      Character:
C      GEOM      : a single character variable for channel geometry.
C      UNIT      : a single character variable for unit.
C      FLUID     : a single character variable for fluid type.
C      ORIENT    : a single character variable for channel orientation.
C      STATE     : a single character variable for state of the system.
C
C      Real:
C      X         : provided quality.
C      D         : provided diameter.
C      G         : provided mass flux.
C      P         : provided pressure.
C      INIRP3    : the interpolated value.
C      PX        : discrete value of quality.
C      PG        : discrete value of mass flux.
C      PP        : discrete value of pressure.
C      CHFTAB    : a set of 4410 discrete values of CHF arranged in three-
C                  dimensional arrays.
C
C      Logical:
C      NFLG      : Program termination flag.
C      Flag      : Step termination flag.
C
C*****

```

```

REAL CHFTAB(21,14,15),PX(21),PG(14),PP(15),INIRP3
LOGICAL FLAG

```

```

C*****
C
C      Call up two common blocks to pass some variables in and out the *
C      subroutine. *
C *
C*****

COMMON/TABLE/CHFTAB
COMMON/ROWS/PX,PG,PP,IX,IG,IP
      PH2O = P
      GH2O = G

C*****
C
C      Initialize the flag and range pointer. *
C *
C*****

      FLAG = .TRUE.
      IX = 20
      IG = 13
      IP = 14

C*****
C
C      Locate the discrete value of quality bounding the input value. *
C *
C*****

      DO 100 I=1,20
        IF((X .LE. PX(I+1)) .AND. FLAG)THEN
          IX = I
          FLAG = .FALSE.
        END IF
      100 CONTINUE

C*****
C
C      Re-initialize the flag. *
C      Locate the discrete value of mass flux bounding the input value. *
C *
C*****

      FLAG = .TRUE.
      DO 200 I=1,13
        IF((GH2O .LE. PG(I+1)) .AND. FLAG)THEN
          IG = I
          FLAG = .FALSE.
        END IF
      200 CONTINUE

```

```

C*****
C
C      Re-initialize the flag.
C      Locate the discrete value of pressure bounding the input value.
C
C*****

      FLAG = .TRUE.
      DO 300 I=1,14
        IF((PH2O .LE. PP(I+1)) .AND. FLAG)THEN
          IP = I
          FLAG = .FALSE.
        END IF
      300 CONTINUE

C*****
C
C      Calculate modification factor for tube diameter other than 0.008.*
C
C*****

      IF(D .GT. 0.016)THEN
        CK1 = 0.7937
      ELSE IF(D .LT. 0.002)THEN
        CK1 = 1.5874
      ELSE
        CK1 = (0.008/D)**(1./3)
      END IF
      CHF = INT3P(X, GH2O, PH2O)*CK1*1000
      RETURN
      END

```

REAL FUNCTION INIRP3(X,G,P)

```

C*****
C
C      Function INIRP3
C
C      This function is used to set up the parameters for linear
C      interpolation in CHF evaluation. The parameters are the slope,
C      and two boundary points.
C
C*****

```

```

C*****
C
C      Variable declaration:
C
C      Real:
C      X      : provided quality.
C      G      : provided mass flux.
C      P      : provided pressure.
C      INTERP : the interpolated value.
C      PX     : discrete value of quality.
C      PG     : discrete value of mass flux.
C      PP     : discrete value of pressure.
C , CHFTAB   : a set of 4410 discrete value of CHF arranged in three-
C              dimensional arrays.
C
C*****

```

REAL INTERP,CHFTAB(21,14,15),PX(21),PG(14),PP(15)

```

C*****
C
C      Call up two common blocks to pass some variables in and out the
C      subroutine.
C
C*****

```

COMMON/TABLE/CHFTAB
COMMON/ROWS/PX,PG,PP,IX,IG,IP

```

C*****
C
C      Linear interpolate the pressure value.
C
C*****

```

```

PARAM = (P-PP(IP))/(PP(IP+1)-PP(IP))
C1     = INTERP(CHFTAB(IX,IG,IP),CHFTAB(IX,IG,IP+1),PARAM)
C2     = INTERP(CHFTAB(IX,IG+1,IP),CHFTAB(IX,IG+1,IP+1),PARAM)
C3     = INTERP(CHFTAB(IX+1,IG,IP),CHFTAB(IX+1,IG,IP+1),PARAM)
C4     = INTERP(CHFTAB(IX+1,IG+1,IP),CHFTAB(IX+1,IG+1,IP+1),PARAM)

```

```

C*****
C
C      Linear interpolate the mass flux value.
C
C*****

      PARAM = (G-PG(IG))/(PG(IG+1)-PG(IG))
      C5     = INTERP(C1,C2,PARAM)
      C6     = INTERP(C3,C4,PARAM)

C*****
C
C      Linear interpolate the quality value.
C
C*****

      PARAM = (X-PX(IX))/(PX(IX+1)-PX(IX))
      INTRP3 = INTERP(C5,C6,PARAM)
      RETURN
      END
      REAL FUNCTION INTERP(A1,A2,P)

C*****
C
C      Function INTERP
C
C      This function is used to interpolate value linearly.
C      It requires the slope of the function and two boundary points.
C
C*****

C*****
C
C      Variable declaration:
C
C      Real:
C      INTERP : the interpolated value.
C      P      : slope of the function.
C      A1,A2  : the two bounds.
C
C*****

      INTERP = A1 + (A2-A1)*P
      RETURN
      END

```