AN ASSESSMENT OF TWO-PHASE PRESSURE DROP CORRELATIONS FOR STEAM-WATER SYSTEMS

by

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ABSTRACT

Eighteen two-phase friction pressure drop models and correlations are compared to 2220 experimental steam-water pressure drop measurements under adiabatic conditions and 1230 in diabatic flow conditions. The data represents several geometries and has the following property ranges:

Pressure	250 - 1500 psia
Mass Velocity	$.2\text{x}10^6 - 3.2\text{x}10^6 \text{lbm/hr-ft}^2$
Quality	subcooled to 1.0
Equivalent Diameters	.09 - 1.3 in.

The four models and correlations that coincided most nearly to the entire data collection were the Baroczy correlation, the Thom correlation and the homogeneous model two-phase friction multipliers,

$$\phi_{fo}^2 = \left[1 + x\left(\frac{v_{fg}}{v}\right)\right]$$

and

$$\phi_{fo}^2 = \left[1 + x\left(\frac{v_{fg}}{v}\right)\right]\left[1 + x\left(\frac{\mu_g}{\mu_f}\right) - 1\right]^{.25} .$$

The correlations are also evaluated with the data being subdivided into sets which are based on properties.

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NOMENCLATURE

A	flow area
A_f	flow area of liquid phase
A_g	flow area of vapor phase
a	parameter in equation (4.13)
B	parameter in equation (4.66) and given in table 4.7
C	parameter in equations (4.25) and (4.66) and given in table 4.1
c_p	specific heat
D	diameter
D_g	equivalent diameter of the vapor phase flow
D_e	equivalent diameter
D_f	equivalent diameter of the liquid phase flow
$F(x)$	parameter defined by equation (4.62)
f	friction factor
f_f	friction factor based on actual liquid flow
f_{fo}	friction assuming entire flow to be liquid
f_g	friction factor based on actual vapor flow
f_{tp}	friction factor appropriate to two-phase flow condition
G	mass velocity
G_f	mass velocity of the liquid phase
G_g	mass velocity of the vapor phase
g	gravitational acceleration
g_c	gravitational constant

h	specific enthalpy
h_f	specific enthalpy of saturated liquid
h_{fg}	latent heat of vaporization
h_{in}	inlet specific enthalpy
h_{losses}	specific enthalpy loss in test section
K	numerical coefficient
K_f	numerical coefficient relevant to liquid phase
K_g	numerical coefficient relevant to vapor phase
L	length
m	parameter in equation (4.13)
m	numerical exponent
m_i	value of variable v_i
N	number of data points
n	numerical exponent
P	pressure
Q	volumetric flow rate
Q_g	Volumetric flow rate of the vapor phase
Q_f	Volumetric flow rate of the liquid phase
R	example function for uncertainty analysis
r	radius
Re	Reynolds number
Re_f	Reynolds number based on actual liquid flow
Re_{fo}	Reynolds number assuming entire flow to be liquid
Re_g	Reynolds number based on actual vapor flow
S	slip ratio
T_{in}	inlet temperature
u	flow velocity

u_f	velocity of the liquid phase
u_g	velocity of the vapor phase
u_{max}	maximum local velocity
$\bar{u}$	mean velocity
v	specific volume
v_f	specific volume of saturated liquid
v_{fg}	$v_g - v_f$
v_g	specific volume of saturated vapor
$\bar{v}$	mean specific volume
v_i	example variable for uncertainty analysis
W	mass flow rate
W_f	liquid phase mass flow rate
W_g	vapor phase mass flow rate
W_i	uncertainty interval for variable v_i
X	Lockhart-Martinelli parameter
x	mass quality
x_{in}	inlet mass quality
x_{out}	exit mass quality
y	distance from duct boundary
z	distance along flow path
$\left(\frac{dP}{dz}\ a\right)$	pressure gradient due to acceleration
$\left(\frac{dP}{dz}\ F\right)$	pressure gradient due to friction
$\left(\frac{dP}{dz}\ F\right)_f$	friction pressure gradient assuming actual liquid flow

$\left(\frac{dP}{dz}\,F\right)_{fo}$	friction pressure gradient assuming entire flow to be liquid
$\left(\frac{dP}{dz}\,F\right)_{g}$	friction pressure gradient assuming actual vapor flow
$\left(\frac{dP}{dz}\,fF\right)$	friction pressure gradient in the liquid phase
$\left(\frac{dP}{dz}\,gF\right)$	friction pressure gradient in the vapor phase
$\left(\frac{dP}{dz}\,z\right)$	pressure gradient due to static head
α	void fraction
α_{LOCAL}	void fraction at a point in a flow
α_{MAX}	maximum local void fraction
β	volumetric quality
Γ	Chisholm property index
γ	ratio of liquid flow area to area calculated using the liquid flow equivalent diameter
ΔP	pressure drop
ΔP_a	acceleration pressure drop
ΔP_f	friction pressure drop
ΔP_{fsc}	friction pressure drop in subcooled region
ΔP_z	static head pressure drop
δ	film thickness
δ	ratio of vapor flow area to area calculated using the vapor flow equivalent diameter
$\delta\underline{\quad}$	uncertainty interval for variable $\underline{\quad}$
$\delta x_{\underline{\quad}}$	uncertainty interval for quality due to uncertainty in variable $\underline{\quad}$

$\left(\dfrac{\delta\phi_{fo}^2}{\phi_{fo}^2}\right)_{\_\_}$	uncertainty interval for two-phase friction multiplier divided by multiplier, due to uncertainty in variable __
ε	discrepancy between data and correlation defined by equation (5.1)
ε_{RMS}	root-mean-square value of for N data points
σ	angle of flow inclination
λ	parameter used in figure 2.4 and given by figure 2.5
μ	viscosity
μ_f	saturated liquid viscosity
μ_g	saturated vapor viscosity
$\bar{\mu}$	mean viscosity
ρ	density
ρ_f	saturated liquid density
ρ_g	saturated vapor density
$\bar{\rho}$	mean density
σ	surface tension
σ_i	standard deviation of variable i
τ	shear stress
τ_f	shear stress based on actual liquid flow
τ_o	wall shear stress
τ_{tp}	shear stress under two-phase flow conditions
Φ_1	heat flux from boiler or preheater
ϕ_f^2	two-phase friction multiplier based on actual liquid flow
ϕ_{fo}^2	two-phase friction multiplier assuming the entire flow to be liquid
ϕ_g^2	two-phase friction multiplier based on the actual vapor flow

Ψ	parameter used in figure 2.4 and given in figure 2.5
Ω	correlation adjustment factor
$\bar{\phi}^2_{fo}$	average two-phase multiplier for diabatic conditions

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Chapter 1

INTRODUCTION

In the operation of fluid energy conversion systems, such as boilers and nuclear reactors, two-phase flow phenomena occur by design or can happen in an accident situation. Presently, nearly all such systems use water or water and steam as the working fluid. Consequently, the ability to accurately predict the pressure drop in a steam-water flow is important in the design of such systems. For nuclear systems, knowledge of the portion of the flow not occupied by the liquid is very critical to the proper design of the reactor core.

A completely acceptable analytical model of the two-phase pressure drop has never been developed causing reliance to be placed on empirical methods as the means to predict the pressure drop. Several semi-analytical models and empirical correlations for two-phase pressure drop have been developed since World War II, most being stimulated by the growth of nuclear power systems. Eighteen prediction methods are reviewed in this study. These include the most common and reputed correlations and models. Some 3450 steam-water pressure drop data points were collected for comparison with the predictions.

Even though this study does not cover void fraction models and correlations, their application in the reduction of pressure drop data and in some pressure drop correlations justifies covering them. Consequently, the review of two-phase correlations includes several void fraction predictions. This study also notes the effects of using different void fraction correlations to reduce the pressure drop data.

The ultimate objective of this work is to provide recommendations regarding the suitability of the various methods of predicting the two phase pressure drop.

Chapter 2

PRELIMINARY CONCEPTS

2.1 Void Fraction and Quality

The local void fraction is the time averaged volumetric fraction of the vapor phase at a point in a two-phase flow. The void fraction of the entire flow at a given cross section is the area average of the local void fractions for that section or

$$\alpha \equiv \frac{1}{A} \int_A \alpha_{LOCAL} \, dA. \tag{2.1}$$

Put in other words, it is the ratio of the time averaged area occupied by the vapor phase to the total area of the cross section,

$$\alpha \equiv \frac{A_g}{A_g + A_f} . \tag{2.2}$$

The requirements for mass continuity must hold for each phase of the flow. The mass flux for each phase is written

$$W_f = \rho_f A_f u_f \tag{2.3a}$$

and

$$W_g = \rho_g A_g u_g . \tag{2.3b}$$

The volumetric flow rates for each phase are defined as

$$Q_f \equiv u_f A_f \tag{2.4a}$$

and

$$Q_g \equiv u_g\ A_g. \tag{2.4b}$$

Dividing equation (2.3) by the total cross section area yields the mass velocities for each phase

$$G_f = u_f\ \rho_f\ (1-\alpha) \tag{2.5a}$$

and

$$G_g = u_g\ \rho_g\ \alpha. \tag{2.5b}$$

The flowing mass and volumetric qualities are defined as

$$x \equiv \frac{W_g}{W_g + W_f} \tag{2.6}$$

and

$$\beta \equiv \frac{Q_g}{Q_g + Q_f}, \tag{2.7}$$

respectively. The flowing mass quality is not necessarily equal to the thermal equilibirum mass quality as determined by an energy balance. They are equal in the case of thermal equilibrium between the two phases, and under non-equilibrium conditions they are very nearly so, except in cases of extreme thermal gradients such as occur in subcooled boiling and film boiling.

Equation (2.3) can be rewritten as

$$W_f = W\ (1-x) \tag{2.8a}$$

and

$$W_g = Wx, \tag{2.8b}$$

which divided by the total flow area gives

$$G_f = G\,(1-x) \tag{2.9a}$$

and

$$G_g = Gx. \tag{2.9b}$$

The parameters defined by equations (2.2), (2.6) and (2.7) can be related to each other through appropriate substition of equations (2.3), (2.4), (2.5), (2.8) and (2.9) by

$$\left(\frac{1-\alpha}{\alpha}\right) = \left(\frac{u_g}{u_f}\right)\left(\frac{\rho_g}{\rho_f}\right)\left(\frac{1-x}{x}\right), \tag{2.10}$$

$$\left(\frac{1-\alpha}{\alpha}\right) = \left(\frac{u_g}{u_f}\right)\left(\frac{1-\beta}{\beta}\right) \tag{2.11}$$

and

$$\left(\frac{1-x}{x}\right) = \left(\frac{\rho_f}{\rho_g}\right)\left(\frac{1-\beta}{\beta}\right). \tag{2.12}$$

The ratio of the gas phase velocity to that of the liquid phase defines the slip ratio,

$$S \equiv \frac{u_g}{u_f}. \tag{2.13}$$

A knowledge of the slip ratio and the flowing mass quality is required to determine the void fraction by equation (2.10).

2.2 Flow Regimes

A two-phase flow appears in several different patterns depending on the relative amounts of liquid and vapor present, the velocities of the phases, pressure, flow orientation, and rate of heat addition. Figures 2.1 and 2.2 depict the appearance of several of the flow patterns. The reader is referred to basic two-phase flow texts [1, 2, 3] for details about the various flow regimes. Figures 2.3 and 2.4 are generally accepted flow regime maps for vertical and horizontal flows. Figure 2.5 give the values of the variables Ψ and λ that are to be used in figure 2.4 for steam-water systems.

2.3 Pressure Drop

By manipulating the conservation of momentum or energy relations [1] for a steady state two-phase flow it can be shown that the pressure gradient for such a flow is the sum of the pressure gradients due to friction, acceleration resulting from a change in volume of the flow and gravity,

$$\frac{dP}{dz} = \left(\frac{dP}{dz}\,F\right) + \left(\frac{dP}{dz}\,a\right) + \left(\frac{dP}{dz}\,z\right). \qquad (2.14)$$

The friction component can be computed using the familiar Fanning equation

$$\left(\frac{dP}{dz}\,F\right) = -\,\frac{2\,f_{tp}\,G^2\bar{v}}{g_c D}, \qquad (2.15)$$

where f_{tp} is a friction factor which is relevant to the two-phase flow condition and $\bar{v}$ is the spatial mean specific volume. The acceleration term is

$$\left(\frac{dP}{dz}\,a\right) = -\,\frac{G^2}{g_c}\,\frac{d\bar{v}}{dz} \qquad (2.16)$$

and the pressure gradient caused by a change in elevation is given by

$$\left(\frac{dP}{dz}\,z\right) = -\,\frac{g\,\sin\theta}{g_c\,\bar{v}}. \qquad (2.17)$$

Further modeling of the flow is required to be able to evaluate the mean specific volume and friction factor.

The two basic models are known as the homogeneous model and the separated flow model. They will be covered in greater detail in a subsequent chapter.

Equation (2.15) is of the same form as the friction pressure gradient for a single phase flow. Consequently, the unknown terms f_{tp} and $\bar{v}$ are some multiple of the comparable single phase terms and, thus, it has become convenient to express the friction gradient as that for a single phase flow multiplied by an appropriate value. This is true for both models of two-phase flow. The primary difference in the two models is the evaluation of the acceleration and gravity pressure gradients.

2.4 Two-Phase Friction Multiplier

As noted in the previous section, it has become convenient to express the two-phase friction pressure gradient as a single phase friction gradient multiplied by an appropriate function of the flow parameters. This function has become known as the two-phase friction multiplier, three common forms of which are defined as

$$\phi_{fo}^2 \equiv \frac{\left(\frac{dP}{dz}\,F\right)}{\left(\frac{dP}{dz}\,F\right)_{fo}}, \tag{2.18}$$

$$\phi_f^2 \equiv \frac{\left(\frac{dP}{dz}\,F\right)}{\left(\frac{dP}{dz}\,F\right)_{f}} \tag{2.19}$$

and

$$\phi_g^2 \equiv \frac{\left(\frac{dP}{dz}\ F\right)}{\left(\frac{dP}{dz}\ F\right)_g}, \qquad (2.20)$$

where

$$\left(\frac{dP}{dz}\ F\right)_{fo} = -\ \frac{2\ f_{fo}\ G^2\ v_f}{g_c\ D}, \qquad (2.21)$$

$$\left(\frac{dP}{dz}\ F\right)_f = -\ \frac{2\ f_f\ G_f^2\ v_f}{g_c\ D} \qquad (2.22)$$

and

$$\left(\frac{dP}{dz}\ F\right)_g = -\ \frac{2\ f_g\ G_g^2\ v_g}{g_c D}. \qquad (2.23)$$

The gradient in equation (2.2) presumes that the entire flow is liquid. Equation (2.22) is based on the actual liquid flow and equation (2.23) is based on the actual gas flow.

If it is assumed that the friction factor is of the Blasius solution type

$$f = \frac{.079}{Re^{.25}}, \qquad (2.24)$$

the two phase multipliers can be related to each other by appropriate substitutions, so that

$$\phi_{fo}^2 = \phi_f^2\ (1-x)^{1.75} = \phi_g^2 \left(\frac{v_g}{v_f}\right)\left(\frac{\mu g}{\mu_f}\right)^{.25} x^{1.75}. \qquad (2.25)$$

2.5 Friction Factors

Evaluation of equations (2.21), (2.22) and (2.23) requires the selection of an appropriate friction factor. As will be noted in subsequent chapters, experimenters have used different forms of the friction factor. The familiar Blausius solution friction factors

$$f = \frac{.046}{Re^{.2}} \qquad (2.26)$$

and

$$f = \frac{.079}{Re^{.25}}. \qquad (2.27)$$

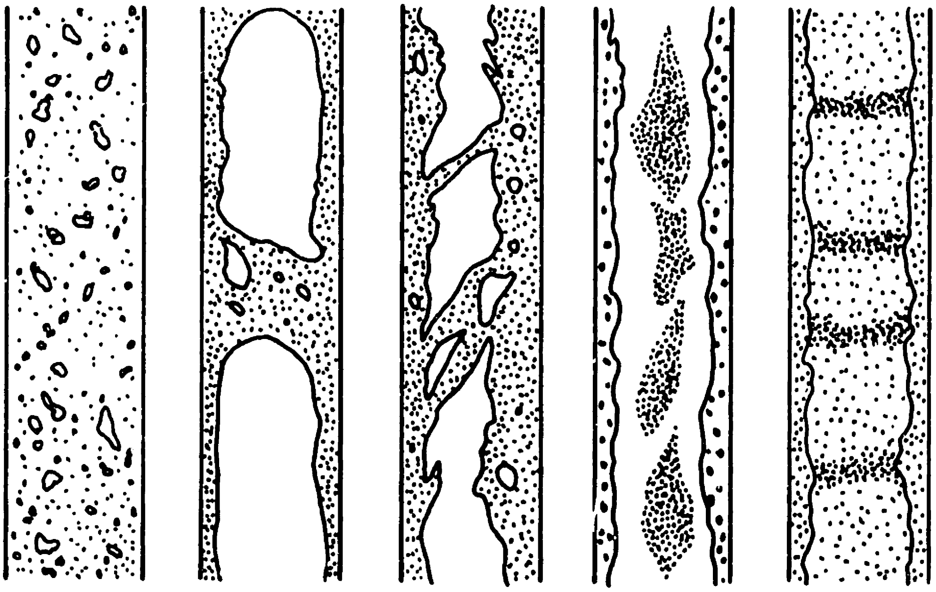
are good approximations for the smooth pipe friction factor which can be expressed as

$$\frac{1}{\sqrt{f}} = 4.0 \log_{10} [Re\sqrt{f}] - .4. \qquad (2.28)$$

Equation (2.27) is the more valid approximation for Reynolds numbers up to 50,000 and equation (2.26) applies for greater Reynolds numbers. Two-phase steam-water data reviewed in this study ranges in liquid-only Reynolds numbers from 20,000 to 600,000. At this upper limit the friction factor computed by equation (2.27) is 15 percent less than that obtained by equation (2.26).

Some investigators have used friction factors that reflect the hydraulic roughness of their test apparatus. These friction factors are based on tests conducted on the equipment under single phase conditions.

In order to make estimates of the pressure drop during design calculations for boiling systems, a selection of an acceptable friction factor must be made. Wallis [2] contends that a single phase friction factor of .005 is "adequate" to compute the friction pressure gradient by equations (2.21) or (2.22) for common two-phase systems. Experimenters, for instance Macbeth [22], have concluded that surface finish and deposits have negligible effects on the pressure drop of boiling systems. Over the range of data reviewed in this study, the liquid only smooth pipe friction factors range from .003 to .007. Collier uses smooth pipe approximations in the examples in his text [1]. There is certainly a degree of arbitrariness in the selection of a friction factor. In performing pressure drop calculations a friction factor equal to or greater than that of the smooth pipe case would normally be selected to make the computation. If the two-phase friction multiplier used is based on data which has been reduced using the smooth pipe condition, then the calculation should give results equivalent to or more conservative than the data on which the correlation is based. Consequently, it is considered appropriate to use the smooth tube friction factor or the appropriate approximation in reducing two-phase pressure drop data and making predictions.



Bubbly

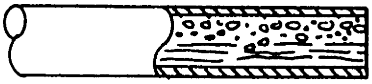
Slug

Churn

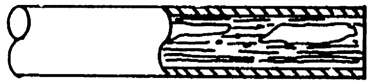
Wispy – annular

Annular

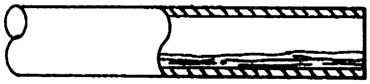
Figure 2.1 Flow Patterns in Vertical Flow [1]



Bubbly



Plug



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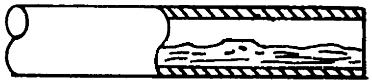
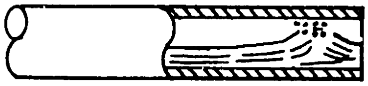
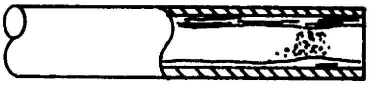


Wavy



Slug



Annular

Figure 2.2 Flow Patterns in Horizontal Flow [1]

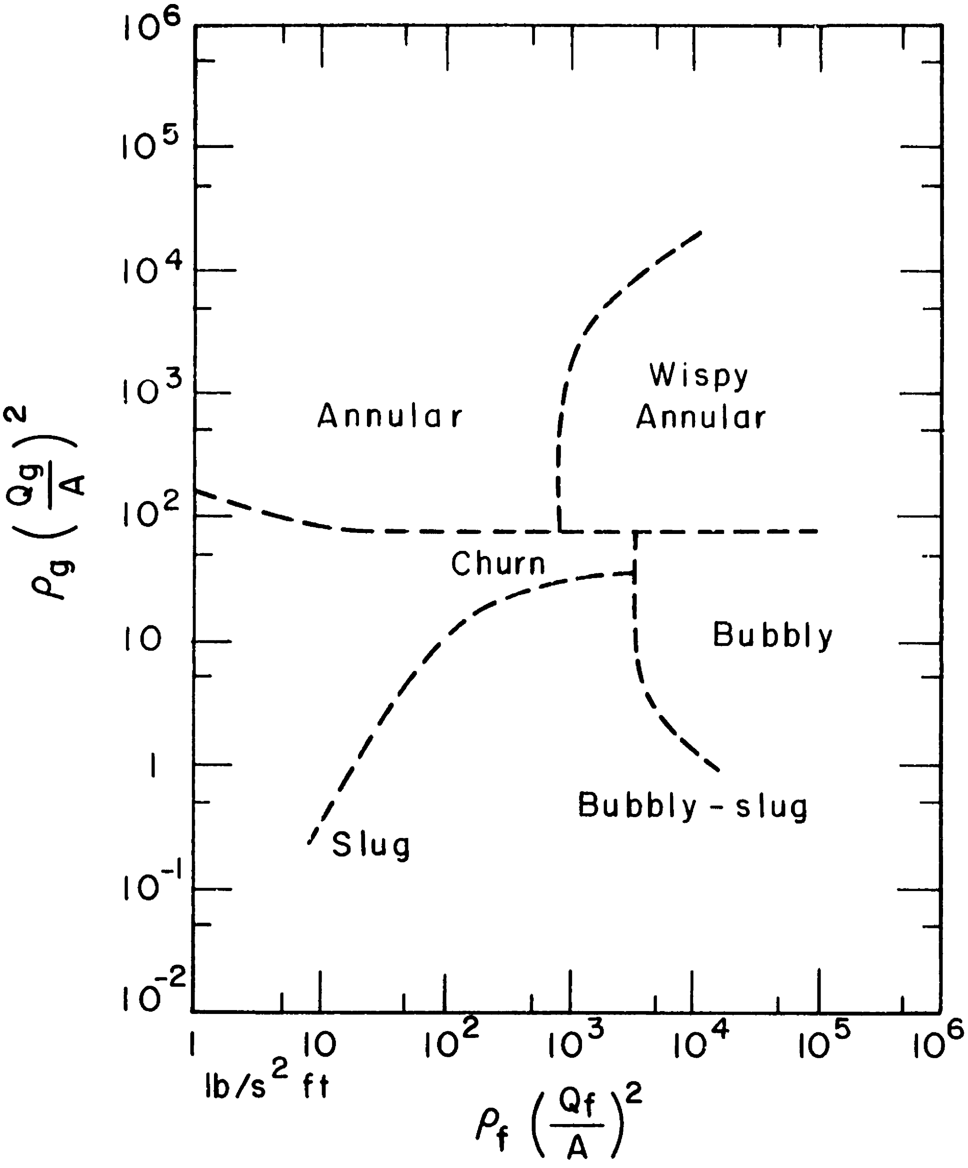


Figure 2.3 Vertical Flow Regime Map [1]

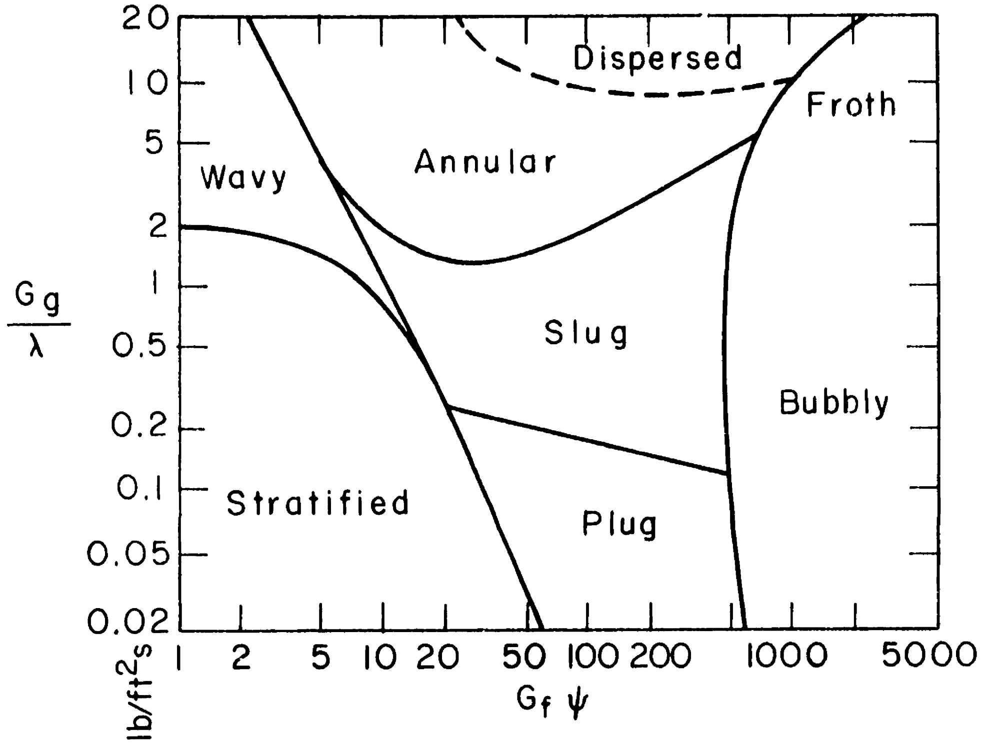


Figure 2.4 Horizontal Flow Regime Map [23]

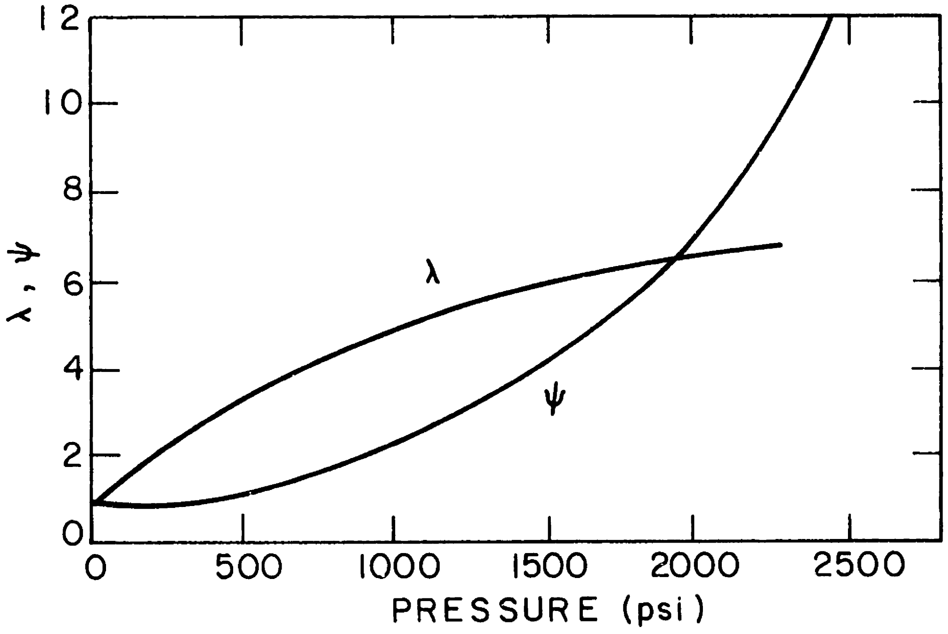


Figure 2.5 Values of λ and ψ for Steam-Water Systems for use with Figure 1.4 [1]

Chapter 3

THE BASIC TWO-PHASE FLOW MODELS

3.1 The Homogeneous Model

The homogeneous model is based on the assumption that both the liquid and vapor phases have the same velocity and are in thermal equilibrium. Thus, the slip ratio for this model is unity. The average specific volume is the volumetric flow rate divided by the mass flow rate,

$$\bar{v} = \frac{Q}{W}. \tag{3.1}$$

Substituting equations (2.3), (2.6), (2.7) and (2.12) into equation (3.1) gives

$$\bar{v} = xv_g + (1-x)v_f. \tag{3.2}$$

By substituting this relationship into equations (2.14) through (2.17), the two-phase pressure gradient can be written, assuming the liquid phase to be incompressible, as

$$\frac{dP}{dz} = -\frac{\dfrac{2f_{tp}G^2v_f}{g_cD}\left[1+x\left(\dfrac{v_{fg}}{v_f}\right)\right] + \dfrac{G^2v_f}{g_c}\,\dfrac{v_{fg}}{v_f}\left(\dfrac{dx}{dz}\right) + \dfrac{g}{gc}\,\dfrac{\sin\Theta}{\left[1+x\left(\dfrac{v_{fg}}{v_f}\right)\right]}}{\left[1+\dfrac{G^2}{g_c}\,x\left(\dfrac{dv_g}{dP}\right)\right]}. \tag{3.3}$$

At the pressures and mass velocities of steam-water systems of engineering importance the denominator of equation (3.3) is very nearly one. Based on this assumption equation (3.3) can be reduced to

$$\frac{dP}{dz} = -\frac{2f_{tp}G^2v_f}{G_cD}\left[1+x\left(\frac{v_{fg}}{v_f}\right)\right] - \frac{G^2v_f}{g_c}\left(\frac{v_{fg}}{v_f}\right)\frac{dx}{dz} - \frac{g\ \sin}{g_c\left[1+x\left(\frac{v_{fg}}{v_f}\right)\right]}. \tag{3.4}$$

Equation (3.4) can be integrated for flows with simple quality distributions. It can also be used in the gradient form for step-by-step solutions.

Evaluation of the friction term of equation (3.4) requires the selection of an appropriate friction factor. One method is to use the friction factor calculated on the basis of the entire flow being liquid only. Then

$$\left(\frac{dP}{dz}\ F\right) = -\frac{2f_{fo}G^2v_f}{G_cD}\left[1+x\left(\frac{v_{fg}}{v_f}\right)\right] \tag{3.5}$$

for which the two-phase friction multiplier as defined by equations (2.18) and (2.21) is

$$\phi_{fo}^2 = 1 + x\left(\frac{v_{fg}}{v_f}\right). \tag{3.6}$$

Another method of computing the two-phase pressure gradient using the homogeneous model is to use a friction factor which tends to the appropriate limits as the flow approaches all vapor or liquid conditions, for instance, a Blasius solution friction factor,

$$f_{tp} = \frac{.079}{\left(\frac{GD}{\bar{\mu}}\right)^{.25}} \tag{3.7}$$

can be used for this case if

$$\bar{\mu} \rightarrow \mu_f \quad \text{as} \quad x \rightarrow 0$$

and

$$\bar{\mu} \rightarrow \mu_g \quad \text{as} \quad x \rightarrow 1.$$

Collier [1] cites three relations for a two-phase viscosity which satisfy the above requirements. They are

$$\frac{1}{\bar{\mu}} = \frac{x}{\mu_g} + \frac{1-x}{\mu_f}, \tag{3.8}$$

$$\bar{\mu} = x\mu_g + (1-x)\ \mu_f \tag{3.9}$$

and

$$\bar{\mu} = [xv_g\mu_g + (1-x)\ v_f\mu_f]. \tag{3.10}$$

These three equations when combined with the friction term of equation (3.4) and the two-phase multiplier definition yield

$$\phi^2_{fo} = \left[1 + x\left(\frac{v_{fg}}{v_f}\right)\right]\left[1 + x\left(\frac{\mu_f}{\mu_g} - 1\right)\right]^{-.25}, \tag{3.11}$$

$$\phi^2_{fo} = \left[1 + x\left(\frac{v_{fg}}{v_f}\right)\right]\left[1 + x\left(\frac{\mu_g}{\mu_f} - 1\right)\right]^{.25} \tag{3.12}$$

and

$$\phi^2_{fo} = \left[1 + x\left(\frac{v_{fg}}{v_f}\right)\right]\left[\frac{xv_g\left(\frac{\mu_g}{\mu_g}\right) + (1-x)v_f}{xv_g + (1-x)v_f}\right]^{.25}. \tag{3.13}$$

The void fraction for the homogeneous model can be calculated using equation (2.10) with the slip ratio being unity. The homogeneous model is considered more appropriate for flow patterns, such as bubbly and wispy annular flows at high linear velocities and pressures [1]. These flow conditions tend to meet the model assumptions. However, the homogeneous model is frequently applied without regard to flow regime and conditions.

3.2 The Separated Flow Model

This model is not restricted to the condition that phase velocities be equal as is the homogeneous model and so it would tend to be most appropriate for flows having a substantial difference in the phase velocities such as the annular flow pattern [1]. Assuming that the remaining conditions with which equation (3.4) was developed are applicable to this model, the pressure gradient for separated flow is

$$\frac{dP}{dz} = \left(\frac{dP}{dz}\,F\right) - \frac{G^2}{g_c}\frac{d}{dz}\left[\frac{x^2 v_g}{\alpha} + \frac{(1-x)^2}{1-\alpha}v_f\right] - \frac{g\sin\Theta}{g_c}\left(\rho_g\alpha + (1-\alpha)\,\rho_f\right) \tag{3.14}$$

where

$$\frac{dP}{dz}\,F = \left(\frac{dP}{dz}\,F\right)_{fo}\phi_{fo}^2. \tag{3.15}$$

To apply this result one must know the void fraction and two-phase friction multiplier. This result does reduce to the homogeneous model if a slip ratio of one is applied. Equation (3.14) can be readily integrated for a linear quality profile. It is a simple matter to integrate it by numerical and step-by-step methods for any quality distribution.

The multiplier and void fraction can be obtained from empirical correlations or analytical models which do not restrict the slip ratio to unity. These will be discussed in the following chapter.

Chapter 4

TWO-PHASE FLOW CORRELATIONS

4.1 Introduction

Major two-phase pressure drop and some void fraction correlations and models are reviewed in this chapter. In several cases the void fraction models and correlations are an integral part of the calculation of the two-phase friction multiplier. As noted in the previous chapter, knowledge of the void fraction is necessary to compute the acceleration and elevation pressure gradients when applying the separated flow model. Void fraction models were applied in reducing the data used in this study of pressure drop models. Consequently, it is considered appropriate to review some of the void fraction models in conjunction with the pressure drop correlations.

Different correlators have expressed their results in a variety of forms. Wherever it is convenient in this review, appropriate substitutions have been made to give the result in terms of the two-phase friction multiplier which is based on the entire flow being liquid as defined by equation (2.18).

4.2 The Armand Correlation [4]

The Armand correlation has its basis in a model of an annular flow having all of the liquid phase forming a film of constant thickness, δ, along the wall of a circular pipe of radius, r. The film thickness then can be expressed as

$$\delta = r(1 - \sqrt{\alpha}). \tag{4.1}$$

The velocity profile in the liquid film is assumed to obey the Prandtl-Tietjens law of the seventh root

$$u_f = K \left(\frac{\tau_o g_c}{\rho_f} \right)^{4/7} \left(\frac{\rho_f y}{\mu_f} \right)^{1/7} \tag{4.2}$$

where K is a numerical coefficient. The shear forces acting on a differential length of the pipe are in equilibrium with the forces resulting from the pressure drop over that differential length, or

$$2\pi r \tau_o dz = \pi r^2 dP. \tag{4.3}$$

Combining equations (4.1), (4.2) and (4.3) with the continuity requirements for the liquid film,

$$W_f = 2\pi\rho_f \int_o^\delta u_f (r-y) dy, \tag{4.4}$$

y being the distance inward from the wall, and the definition of the single phase pressure drop, assuming the actual liquid flow rate, as given by equation (2.22) results in

$$\left(\frac{dP}{dz} F \right) = \left(\frac{dP}{dz} F \right)_f \frac{K}{(1-\sqrt{\alpha})^2 \; (1 + \frac{8}{7} \sqrt{\alpha})^{7/4}}, \tag{4.5}$$

K being a numerical coefficient. The denominator of equation (4.5) is approximated as

$$(1-\sqrt{\alpha})^2 \; (1 + \frac{8}{7} \sqrt{\alpha})^{7/4} \simeq K(1-\alpha)^2, \tag{4.6}$$

and then

$$\left(\frac{dP}{dz}\,F\right) = \left(\frac{dP}{dz}\,F\right)_f \frac{K}{(1-\alpha)^2} \,. \tag{4.7}$$

From this and similar calculations for an annular flow with entrainment Armand concluded that the friction pressure gradient is of the form

$$\left(\frac{dP}{dz}\,F\right) = \left(\frac{dP}{dz}\,F\right)_f \frac{K}{(1-\alpha)^n} \tag{4.8}$$

Armand correlated horizontal flow air-water pressure drop data at pressures around one atmosphere covering a large range of qualities and velocities. His results converted into two-phase friction multipliers, as defined by equation (2.18), are:

$$\phi^2_{fo} = \frac{(1-x)^{1.75}}{(1-\alpha)^{1.42}} \quad \text{for} \quad 0 < \alpha \leq .65 \tag{4.9}$$

$$\phi^2_{fo} = \frac{.478\,(1-x)^{1.75}}{(1-\alpha)^{2.2}} \quad \text{for} \quad .65 < \alpha \leq .9 \tag{4.10}$$

$$\phi^2_{fo} = \frac{1.73\,(1-x)^{1.75}}{(1-\alpha)^{1.64}} \quad \text{for} \quad .9 < \alpha \tag{4.11}$$

The void fraction used by Armand to correlate the pressure drop data is computed by

$$\alpha = .833\,\beta \quad \text{for} \quad \beta < .9 \tag{4.12}$$

and

$$\alpha = 1 - \frac{4 + \frac{8}{7}M}{5 + m\left(\frac{\beta}{1-\beta} + \frac{8}{7}\right)} \quad \text{for} \quad \beta \leq .9 \tag{4.13}$$

where

$$m = 4 \quad Re_f^{\,1/8} \quad \frac{\rho_g}{\mu_f}^{1/2}$$

and

$$a = .69 + (1-\beta) \; (4 + .104 \; W_f).$$

Equations (4.12) and (4.13) were obtained by empirical means.

The correlation was checked against steam-water data at pressures up to 150 psi and found to agree satisfactorily according to the author. Armand acknowledged that the validity of this correlation is limited to the conditions of the data on which it was based. This pressure drop correlation was an option in the COBRA reactor code [7, 8], however, the void fraction was not computed by equations (4.12) and (4.13).

4.3 The Lockhart-Martinelli Correlation [5]

This correlation was presented for flows of these basic categories: liquid phase viscous and gas phase viscous, liquid phase viscous and gas phase turbulent, liquid phase turbulent and gas phase turbulent, and liquid phase turbulent and gas phase viscous. The primary assumptions of the correlation are that the pressure drop of both phases are equal and there are no significant flow pattern changes through the length of the conduit. The data on which this correlation is based was taken in isothermal horizontal flow conditions so that the entire measured pressure drop consisted of only the friction component.

In the derivation of the Lockhart-Martinelli parameter, X, the two-phase friction pressure gradient is set equal to that of the two-phases.

$$\left(\frac{dP}{dz}\ F\right) = \left(\frac{dP}{dz}\ gF\right) = \left(\frac{dP}{dz}\ fF\right). \qquad (4.14)$$

These pressure gradients, assuming a hydraulic diameter for each phase can be written

$$\left(\frac{dP}{dz}\ fF\right) = -\ \frac{2\ f_f\ \rho_f\ u_f^2}{g_c\ D_f} \qquad (4.15a)$$

$$\left(\frac{dP}{dz}\ gF\right) = -\ \frac{2\ f_g\ \rho_g\ u_g^2}{g_c\ D_g}. \qquad (4.15b)$$

The relationships between the area occupied by each phase and their hydraulic diameter are

$$A_f = \gamma\left(\frac{\pi}{4}\ D_f^2\right) \qquad (4.16a)$$

and

$$A_g = \delta\left(\frac{\pi}{4}\ D_g^2\right) \qquad (4.16b)$$

where δ and γ relate the actual phase flow areas to that of a circular flow area of the appropriate diameters. The friction factors may be expressed in the Blasius solution form.

$$f_f = K_f\ \left[\frac{\rho_f\ u_f\ D_f}{\mu_f}\right]^{-m} \qquad (4.17a)$$

and

$$f_g = K_g\ \left[\frac{\rho_g\ u_g\ D_g}{\mu_g}\right]^{-n}. \qquad (4.17b)$$

The phase velocities are

$$u_f = \frac{W_f}{\gamma(\frac{\pi}{4} D_f^2)\rho_f} \tag{4.18a}$$

and

$$u_g = \frac{W_g}{\delta(\frac{\pi}{4} D_g^2)\rho_g}. \tag{4.18b}$$

Substituting equations (4.15) through (4.18) into equation (4.14) gives

$$\left(\frac{dP}{dz} F\right) = \left(\frac{dP}{dz} F\right)_f \gamma^{m-2} \left(\frac{D}{D_f}\right)^{5-m}. \tag{4.19}$$

Applying the definition of the two-phase multiplier as given by equation (2.19) gives

$$\phi_f^2 = \gamma^{m-2} \left(\frac{D}{D_f}\right)^{5-m}. \tag{4.20}$$

Similarly, for the gaseons phase using equation (2.20)

$$\phi_g^2 = \delta^{n-2} \left(\frac{D}{D_g}\right)^{5-n}. \tag{4.21}$$

It is noted that the multipliers are functions of the unknown vaiables γ, δ, D_g and D_f. If a ratio is made of the pressure drops for the liquid and gaseous portions of the flow (equations (4.15a) and (4.15b)), which does equal unity, and appropriate substitutions are made, the result is

$$\frac{D_f^{5-m} \gamma^{2-m}}{D_g^{5-n} \delta^{2-n}} = \frac{K_f W_f^{2-m} \mu_f^m \rho_g}{K_g W_g^{2-n} \mu_g^n \rho_f} \left(\frac{\pi}{4D}\right)^{m-n}. \tag{4.22}$$

The unknown variables of interest are related to determinable variables reflecting the conditions of the flow. The Lockhart-Martinelli parameter X is based on this result. It equals the square root of the right side of equation (4.22) and can be rewritten as

$$X^2 = \frac{Re_g^n \; K_f \; \rho_g \; W_f^2}{Re_f^m \; K_g \; \rho_f \; W_g^2} \tag{4.23}$$

$$X = \frac{\left(\frac{dP}{dz}\; F\right)_f}{\left(\frac{dP}{dz}\; F\right)_g}. \tag{4.24}$$

The values of the exponents and friction constants are dependent on whether the flow for each phase is turbulent or viscous. If the Reynolds number for each phase is greater than 2000 that phase is considered to be flowing turbulently. Table 4.1 gives values of the constants used in equation (4.23) corresponding to the four flow types.

By empirical means the authors related two-phase multipliers as defined by equations (2.19) and (2.20) and void fraction data to the parameter X. These results are given in figure 4.1. Collier [1] cites approximations to these curves. The approximation for the two-phase multiplier is

$$\phi_{fo}^2 = \left[1 - \frac{C}{X} + \frac{1}{X^2}\right] (1-x)^{1.75} \tag{4.25}$$

and for the void fraction is

$$\alpha = 1 - \frac{1}{\left(1 + \frac{20}{X} + \frac{1}{X^2}\right)^{1/2}}. \tag{4.26}$$

The values of C used in these equations for the four flow types are given in table 4.1 also.

The data which supports this correlation is of low pressure adiabatic flows of air and various liquids. The pressure range is from 16 to 50 psia. A wide range of flow rates and dimensions were covered. The authors make no claim of the correlation not being valid in any particular flow conditions, however, they do recognize that data at higher pressures (up to the critical pressures) are needed to establish the validity of this correlation.

4.4 The Martinelli-Nelson Correlation [6]

The stated intention of this correlation is to facilitate the prediction of the pressure drop and void fraction during the forced circulation boiling of water. Only one of the flow conditions, as defined by Lockhart and Martinelli [5], is considered, since practically all forced circulation boiling systems operate with a turbulent gas phase and turbulent liquid phase flow condition. This correlation is tailored to that flow condition.

The Lockhart-Martinelli correlation was developed using data observed in flows at pressures near one atmosphere. This pressure range is assumed to be a longer limit of engineering concern for steam-water systems. The Martinelli-Nelson correlation utilizes the Lockhart-Martinelli results for 14.7 psia. At the critical pressure

$$\left(\frac{dP}{dz}\,F\right) = \left(\frac{dP}{dz}\,F\right)_{fo} \tag{4.27}$$

and, thus, the two-phase multiplier as defined by equation (2.18) is unity.

Having determined values for the limiting pressures, the curves for the intermediate pressures were interpolated with the aid of data taken by Davidson et al [34]. This data was taken in horizontal coils under diabatic conditions at pressures up to 3200 psia. The mass velocities tended to be less than .5 X 10^6 lbm/hr-ft^2 for most of this data.

Martinelli-Nelson give their results as a plot of the two-friction multiplier, ϕ_{fo}^2, as a function of quality and pressure. It is given in figure 4.2. Bowring [10] has tabulated values of the multiplier which are given in table 4.2. The authors also presented their correlation as an average multiplier to be used to determine the pressure drop along a boiling length assuming a linear change in quality. These results will be ignored here since the adiabatic multiplier can be integrated for any desired heat flux distribution by point to point numerical solution on a computer. These average multipliers can be located in reference [6] and basic two-phase flow texts [1, 2, 3].

Martinelli and Nelson also proposed a void fraction correlation. At 14.7 psia it is based on the Lockhart-Martinelli correlation. At the critical pressure the two phases have equal properties and therefore, the void fraction is equal to the quality. Intermediate values were rather arbitrarily interpolated between these extremes. The void fraction correlation is given in figure 4.3.

The authors indicated that their results are tentative and based on only a meager amount of data and that further experimental verification is required before this work is assumed valid. This pressure drop correlation is used in the reactor code HAMBO [10] as an option to the homogeneous model or a polynomial input.

4.5 The Armand-Treschev Correlation [9]

This correlation recognizes that the earlier work by Armand [4] is based on low pressure flows. From equations (2.2) and (2.4) it is seen that the ratio of the volumetric quality to the void fraction is the ratio of the mean vapor phase velocity to that of the total flow,

$$\frac{\beta}{\alpha} = \frac{u_g}{u} \tag{4.28}$$

This ratio can be shown to depend on the density of the two phases by equation (2.10) and (2.11). Since the densities are a function of pressure,

$$\alpha = f(P) \cdot \beta. \tag{4.29}$$

By empirical methods the authors concluded that

$$\alpha = [.833 + .05 \log \frac{P}{14.22}] \ \beta. \tag{4.30}$$

The form of the Armand friction multiplier as given by equation (4.7) is retained for flows with lower void fractions. The empirically determined two-phase friction multipliers are

$$\phi_{fo}^2 = \frac{(1-x)^{1.75}}{(1-\alpha)^{1.2}} \quad \text{for} \quad \alpha < .5, \tag{4.31}$$

and

$$\phi_{fo}^2 = \frac{.48(1-x)^{1.75}}{(1-\alpha)^n} \tag{4.32}$$

where $n = 1.9 + 1.48 \text{ X } 10^{-3} \left(\frac{P}{14.22}\right)$

for $\alpha > .5$ and $\beta < .9$. For high void fractions (more specifically $\beta > .9$)

$$\phi_{fo}^2 = \frac{.0025\left(\frac{P}{14.22}\right) + .055 \quad (1-x)^{1.75}}{(1-\beta)^{1.75}}. \tag{4.33}$$

These relations are based on horizontal, adiabatic steam-water data at pressures ranging from 150 psia - 2700 psia and are considered by the authors to be valid in that range. This correlation supplements Armand's earlier work [4] which is given by equations (4.9), (4.10) and (4.11) and is considered valid at pressures up to 10 atmospheres.

4.6 The Levy Momentum Exchange Model [12]

Levy derived a theoretical model for the void fraction and friction multiplier. The Bernoulli equation for each of the two phases can be written

$$dP_f = \left(\frac{dP}{dz}\, fF\right) dz - \frac{\rho_f u_f du_f}{g_c} - \rho_f (\sin\theta) dz \tag{4.34}$$

and

$$dP_g = \left(\frac{dP}{dz}\, gF\right) dz - \frac{1}{g_c A_g}\, d(A_g \rho_g u_g^2) - \frac{u_f}{g_c A_g} d(A_f \rho_f u_f) - \rho_g (\sin\theta) dz. \tag{4.35}$$

It is assumed that the total pressure drops of the two phases over a given incremental length are equal. Subtracting equation (4.34) from equation (4.35) gives

$$\frac{G^2}{\rho_f g_c}\, d\left[\frac{(1-x)^2}{(1-\alpha)} + \frac{x^2}{\alpha}\left(\frac{\rho_f}{\rho_g}\right) - \frac{1}{2}\,\frac{(1-x)^2}{(1-\alpha)}\right] = \alpha\left[\left(\frac{dP}{dz}\, gF\right) - \left(\frac{dP}{dz}\, fF\right) + (\rho_f - \rho_g)\sin\theta\right] dz \tag{4.36}$$

after substituting equations (2.2), (2.6) and (2.7). If there is no heat addition or flashing the combined friction and elevation pressure drop for each phase must be equal, or

$$\left|\frac{dP}{dz}\,fF\right| dz - \rho_f \sin\theta dz = \left|\frac{dP}{dz}\,gF\right| - \rho_g \sin\theta dz \tag{4.37}$$

and, consequently

$$\frac{(1-x)^2}{1-\alpha} + \frac{x^2}{\alpha}\left(\frac{\rho_g}{\rho_f}\right) - \frac{1}{2}\,\frac{(1-x)^2}{(1-\alpha)^2} = 0. \tag{4.38}$$

Equation (4.38) can be rewritten as

$$x = \frac{\alpha(1-2\alpha)+\alpha\sqrt{(1-2x)+\alpha[2\frac{\rho_g}{\rho_f}(1-\alpha)^2+\alpha(1-2\alpha)]}}{2\frac{\rho_f}{\rho_g}(1-\alpha)+\alpha(1-2\alpha)}. \tag{4.39}$$

The void fraction can be determined from equation (4.39) by an iterative solution. For diabatic flows the right side of equation (4.36) is not equal to zero. In this case, no determinable solution is readily obtainable.

The two-phase friction multiplier proposed by Levy is based on an annular flow model. The two-phase multiplier given by equation (2.19) can be written as a ratio of shear stresses,

$$\phi_f^2 = \frac{\tau_{tp}}{\tau_f} = \frac{f_{tp}\left(\frac{\rho_f u_f^2}{2}\right)}{f_f\left(\frac{\rho_f u_f^2 (1-\alpha)^2}{2}\right)} \tag{4.40}$$

or

$$\phi_f^2 = \frac{f_{tp}}{f_f} \frac{1}{(1-\alpha)^2}. \tag{4.41}$$

The two-phase friction factor is assumed to be related to an equivalent diameter of the film,

$$D_e = \frac{4\pi D\delta}{\pi D} = 4\ \delta. \tag{4.42}$$

The film thickness is related to the tube diameter by

$$\delta = (1-\alpha)\frac{D}{4}. \tag{4.43}$$

The Reynolds number of the film can be written as $(4\delta\rho_f u_f/\mu_f)$ which is equal to the Reynolds number where the liquid only is assumed to be flowing $(G_f D/\mu_f)$. Consequently, friction factors written with these two Reynolds numbers are equal. Applying this result to equation (4.41) and substituting equation (2.25) gives

$$\phi_{fo}^2 = \frac{(1-x)^{1.75}}{(1-x)^2}, \tag{4.44}$$

which is in consonance with the Armand result given in equation (4.7) for the same flow regime model.

Levy compared his pressure drop solution with the Lockhart-Martinelli and Martinelli-Nelson correlations. These agree rather closely when plotted as a function of the void fraction. This model was compared with pressure drop data of several experimenters and deviations of up to fifty percent were noted. The author attributes this to neglecting flow rate effects.

4.7 The Martinelli-Nelson-Jones Correlation [11]

Jones devised an adjustment to the Martinelli-Nelson correlation. The two-phase friction multiplier for this correlation is the Martinelli-Nelson results for the flow of concern multiplied by a factor Ω. The adjustment parameter Ω is empirical and is a function of mass velocity and pressure, and is given by

$$\Omega = 1.36 + .0005P + .1\left(\frac{G}{10^6}\right) - .000714P\left(\frac{G}{10^6}\right) \qquad (4.45)$$

for $G \leq 700{,}000$ lbm/hr-ft^2 and

$$\Omega = 1.26 - .0004P + .119\left(\frac{10^6}{G}\right) + .00028P\left(\frac{10^6}{G}\right) \qquad (4.46)$$

for $G > 700{,}000$ lbm/hr-ft^2.

Jones did not indicate the nature of the data used, nor the range of validity of this factor.

4.8 The Bankoff Variable Density Model [13]

This model is based on the assumption that void fraction and velocity distributions within a flow can be described as

$$\frac{u}{u_{max}} = \left(\frac{Y}{R}\right)^{1/m} \qquad (4.47)$$

and

$$\frac{\alpha}{\alpha_{max}} = \left(\frac{Y}{R}\right)^{1/n} \qquad (4.48)$$

where m and n are unknown constants. Using continuity consideration to determine the mass flow rate, equation (2.2), and determining the average void fraction for the distribution described by equation (4.48) leads to

$$\frac{1}{x} = 1 - \frac{\rho_f}{\rho_g} (1 - \frac{K}{\alpha}) \tag{4.49}$$

where

$$K = \frac{2(m + n + mn) \quad (m + n + 2mn)}{(n + 1) \ (2n + 1) \ (m + 1) \ (2m + 1)}.$$

By substituting equation (2.11) into equation (4.49) it is seen that

$$\alpha = K \beta. \tag{4.50}$$

This coefficient is identical to the coefficients used by Armand [4] and Armand-Treschev [9] as shown in equations (4.12) and (4.29). This result compares favorably to the Martinelli-Nelson void fraction if K is equal to .89. Bankoff found that K depended on pressure as did the aforementioned Russian investigators. By empirical means Bankoff determined that

$$K = .71 + .0001 P. \tag{4.51}$$

Bankoff's pressure drop model is based on the ratio of the two-phase wall shear to that of the liquid phase.

$$\frac{\tau}{\tau_f} = \left(\frac{\bar{\rho}}{\rho_f}\right)^{3/4} \left(\frac{\bar{u}}{u_f}\right)^{7/4} \left(\frac{\bar{\mu}}{\mu_f}\right)^{1/4}. \tag{4.52}$$

The ratio of the densities is

$$\frac{\bar{\rho}}{\rho_f} = 1 - \alpha\left(1 - \frac{\rho_g}{\rho_f}\right) \tag{4.53}$$

and the ratio of the velocities is given as

$$\frac{\bar{u}}{u_f} = 1 - x\left(1 - \frac{\rho_f}{\rho_g}\right). \tag{4.54}$$

Table 4.7

Values of B for Equation (4.66)

Γ	G(lbm/hr-ft^2)	B
≤ 9.5	$\leq 3.69\text{X}10^5$	4.8
	$3.69\text{X}10^5 < G < 1.4\text{X}10^6$	$1.77\text{X}10^6/G$
	$\geq 1.4\text{X}10^6$	$1494/G^{.5}$
$9.5 < \Gamma < 28$	$\leq 4.426\text{X}10^5$	$14123/\Gamma G^{.5}$
	$\leq 4.426\text{X}10^5$	$21/\Gamma$
≥ 28	-	$4.075\text{X}10^5/\Gamma^2 G^{.5}$

The viscosity term is very near unity, consequently equation (4.52) becomes

$$\frac{\tau}{\tau_{sp}} = \left[1 - \alpha\left(1 - \frac{\rho_g}{\rho_f}\right)\right]^{3/4}\left[1 - x\left(1 - \frac{\rho_f}{\rho_g}\right)\right]^{7/4} \qquad (4.55)$$

which is also the two phase friction multiplier as defined by equation (2.18) and can also be written as

$$\phi^2_{fo} = \left[1-\alpha\left(1-\frac{\rho_g}{\rho_f}\right)\right]^{3/4}\left[1-x\left(1-\frac{\rho_f}{\rho_g}\right)\right]^{7/4}(1-x)^{1.75} \qquad (4.56)$$

Bankoff's void fraction model, equation (4.51) with K = .89, agrees well with the Martinelli-Nelson void fraction correlation [6] in the pressure range of 100 to 2500 psia and for void fractions less than .85. The pressure drop model tends to fit the general pattern of the Martinelli-Nelson pressure drop correlation and is considered to agree according to the author even though there may be differences of up to seventy percent between the two.

4.9 The Sze-Foo Chien and Ibele Correlation [14]

This correlation is based on the Lockhart-Martinelli [5] result (equation (4.23)) that the friction multipliers are dependent on the actual liquid and gas flow Reynolds numbers, Re_f and Re_g, respectively. This work gives a friction multiplier which is based on the actual gas flow, ϕ^2_g, which can be related to the two-phase friction multiplier, ϕ^2_{fo}, which is based on the entire flow being liquid by equation (2.25). This correlation is based on annular and annular-mist flow data for air-water vertical down-flow at pressures near one atmosphere.

The friction multipliers are

$$\phi_g^2 = 3.885 \times 10^{-6} \, (Re_g)^{.71} \, (Re_f)^{.725} \tag{4.57}$$

for annular flows and

$$\phi_g^2 = 3.45 \, (Re_g)^{-.34} \, (Re_f)^{.725} \tag{4.58}$$

for annular-mist flows. The transition from annular to annular-mist flow occurs when

$$(Re_g) \, (Re_f)^{.301} = 1.199 \times 10^6. \tag{4.59}$$

No transition into the annular flow regime was determined. Figures 2.2 through 2.4 can be referred to for transition into annular flow.

Equations (4.57), (4.58) and (4.59) were arrived at by empirical methods. The results are shown by the authors to compare favorably with the Lockhart-Martinelli correlation which is based on data taken at similar pressures.

4.10 The Thom Correlation [15]

This correlation is based on steam-water data at pressures from 15-3000 psia. The mass velocities ranged form $.3 \times 10^6$ to 1.4×10^6 lbm/hr-ft^2. The data was taken under both adiabatic and diabatic conditions and vertical and horizontal orientations. The data was taken in earlier boiler circulation studies [33] and provided an adequate data base to correlate friction and void fraction information over the same ranges that Martinelli-Nelson rather arbitrarily interpolated. The results of this work are presented in a similar fashion to the Martinelli-Nelson work.

Thom found that the void fraction data correlated rather satisfactorily if a constant slip ratio δ for a given pressure was assumed. Then equation (2.10) can be used to relate void fraction and quality. Table 4.3 gives the inverse of the slip ratio multiplied by the density ratio as a function of pressure. The resulting void fractions are tabulated in table 4.4 and plotted in figure 4.4, as a function of pressure and quality. The two-phase friction multipliers were based on data and presented in table 4.5, as functions of quality and pressure.

4.11 The Baroczy Correlation [16]

Baroczy noted that the generally accepted pressure drop correlations, namely the Lockhart-Martinelli [5] and the Martinelli-Nelson [6] correlations, do not account for mass velocity effects which are revealed by observed data. It is also noted that these correlations are also limited to either low pressure flows or steam-water flows. The Baroczy correlation was developed to take the mass velocity effects into account and also be applicable to other two-phase systems, as well as steam and water.

This correlation makes the two-phase multiplier a function of a property index which is dependent on pressure alone, with quality as a parameter. This is in keeping with the results of many earlier correlations. To account for the mass velocity effects Baroczy introduced a correction factor for varying mass velocities which is a function of the property index and quality. The mass velocity for the basic correlation is 1 X 10^6 lbm/hr-ft^2. The property index used by Baroczy was the ratio of the liquid only pressure drop to that of a gas only flow and as such is similar to the Lockhart-Martinelli parameter, X. The Baroczy property index is

$$\frac{\left(\frac{dP}{dz}F\right)_{fo}}{\left(\frac{dP}{dz}F\right)_{go}} = \frac{\left(\frac{\mu_f}{\mu_g}\right)^{.2}}{\left(\frac{\rho_f}{\rho_g}\right)}$$

This results in the upper limit of the friction multiplier being the reciprocal of the property index. The property index equals unity at the critical pressure. The friction multipliers are given in figure 4.5 and table 4.6 for the basic mass velocity. The correction factors are given in figure 4.6 for various mass velocities.

The Baroczy correlation is based on the data of several combinations of liquids and gases. The steam-water data used ranges in pressure from 590 to 2000 psia and mass velocities from .7 X 10^6 to 5 X 10^6 lbm/hr-ft^2. This data amounts to about 130 points plus the Sher and Green [24] correlation for 2000 psia. The correlation was compared to the Martinelli-Nelson correlation and found to compare most favorably at low mass velocities. It was also checked against other steam-water data ranging in pressure from 139 to 1400 psia and found to compare favorably.

4.12 The Becker Correlation [17]

Becker and associates conducted two-phase pressure drop experiments in vertical round ducts under diabatic conditions. The pressure profile was plotted and the two-phase multipliers were derived from the gradients of the plot. The results of this work is a correlation of the two-phase multiplier,

$$\phi_{fo}^2 = 1 + 32000\left(\frac{x}{P}\right)^{.96} . \tag{4.60}$$

The supporting data covers a range of pressures from 90 to 600 psia and mass velocites ranging 2×10^5 to 4×10^6 lbm/hr-ft^2. The authors compare their results with the Martinelli-Nelson and Lockhart-Martinelli correlations. This correlation gave results that were as much as 40 percent greater than Martinelli-Nelson's for comparable conditions. It compared favorably with the Lockhart-Martinelli correlation at pressures around 150 psia.

4.13 The Borishansky Correlation [18]

Borishansky and associates concluded that the traditional method of correlating two-phase pressure drop data as a multiplier, being a function of both pressure and quality, may not be the best way to present such data. They chose to correlate pressure drops using

$$\frac{\left(\frac{dP}{dz}F\right) - \left(\frac{dP}{dz}F\right)_{fo}}{\left(\frac{dP}{dz}F\right)_{go} - \left(\frac{dP}{dz}F\right)_{fo}} = F(x). \qquad (4.61)$$

When $x = o$, $F(x) = o$ and when $x = 1$, $F(x) = 1$. The experimental results of the authors indicates the data is sufficiently concentrated so as to be considered independent of heat flux, pressure, geometry and flow rates. $F(x)$ is plotted in figure 4.7.

To allow comparison of this correlation with others, substitution of equations (2.18) and (2.21) and a similar definition of the pressure gradient considering the entire flow to be vapor into equation (4.61) relates $F(x)$ to the two-phase multiplier,

$$\phi^2_{fo} = F(x)\left[\left(\frac{\mu_g}{\mu_f}\right)^{.25}\left(\frac{\rho_f}{\rho_g}\right) - 1\right] + 1. \qquad (4.62)$$

The friction factor is assumed to be given by equation (2.24). $F(x)$ is based on air-water and steam-water data at pressures up to 530 psia.

4.14 The Chisholm Correlation [19]

Chisholm intended this result to be an easier to apply substitute for the Baroczy correlation. He employs a property index similar to the Lockhart-Martinelli parameter X and the Baroczy property index. It is given as

$$\Gamma = \left(\frac{\rho_f}{\rho_g}\right)^{.5}\left(\frac{\mu_g}{\mu_f}\right)^{.5n} \quad \text{for smooth tubes} \qquad (4.63)$$

and

$$\Gamma = \left(\frac{\rho_f}{\rho_g}\right)^{.5} \quad \text{for rough tubes} \qquad (4.64)$$

where n is governed by the appropriate friction factor relation. Chisholm reports that these relations when combined with the approximation of the Lockhart-Martinelli correlation equation (4.25) results in

$$\phi_{fo}^2 = 1 + \left(\Gamma^2 - 1\right) \left[B\left[x(1-x)\right]^{.5(2-n)} + x^{2-n}\right] \qquad (4.65)$$

where

$$B = \frac{C\Gamma - 2^{2-n} + 2}{\Gamma^2 - 1}$$

and C is the same constant as in equation (4.25). Chisholm recommends using empirical values of B which are given in table 4.7. This coefficeint was determined by comparing equation (4.66) to the Baroczy and Lockhart-Martinelli correlations. As a result the significance of C which was used in equation (4.25) to approximate the Lockhart-Martinelli correlation is lost. The values of B determined by Chisholm were intended to give resulting calculations a degree of conservatism.

4.15 The CISE Correlation [20]

During the early 1960's this laboratory conducted and extensive research program in two phase pressure drop. The correlation developed was based on using the homogeneous model to reduce data. The empirical correlation devised is

$$\frac{dP}{dz}_F = \frac{KG^{n} \,^{-.86}\, \sigma^{0.4}}{D^{1.2}} . \qquad (4.66)$$

K and n are given in table 4.8 and are geometry dependent. Equation (4.66) is written for SI or CGS unit systems.

This correlation was obtained from and verified against two-phase vertical pressure drop data in both adiabatic and diabatic conditions. Data for a variety of fluids including steam-water was incorporated into this result. A large range of mass velocities, quality and geometry and pressures up to 1500 psia were covered by the steam-water-data.

4.16 A Summary of the Pressure Drop Correlations and Models

It is noted that different correlations consider different variables. Several depend only on the pressure and quality. Some include the mass velocity and/or the equivalent diameter, in addition. The effects of the mass velocity can be very substantial. A quick glance at figure 4.6, the mass velocity correction factors for the Baroczy correlation, shows that there is a large difference between the friction multipliers for high and low velocity flows. At the same pressure and quality the friction multipliers can vary by as much as a factor of three between low and high velocity flows. Consequently, there can be considerable discrepancy between correlations based on narrow ranges of mass velocities.

There is also a great deal of variety in the methods of the reduction of pressure drop data. Correlators have used data which has appeared in the literature only in a reduced form as a friction multiplier. Table 4.9, which summarizes the correlations presented in this chapter, also shows that a variety of friction factor and void fraction calculations are used in the development and application of correlations. These effects can also cause variation in the pressure drop predictions made by the correlations.

The general applicability of correlations is definitely limited by the data. Several correlations are based on data taken at low pressures. Their validity in cases of high pressure is dubious. The comparison with actual data as reviewed in subsequent chapters will give an indication of the limits of suitability of these works for steam-water systems.

Table 4.1

Lockhart-Martinelli Correlation Constants

Flow Type	Subscript	Reynolds Number Range	K_f	K_g	m	n	C
Gas Viscous Liquid Viscous	vv	$Re_g<1000$ $Re_f<1000$	16	16	1	1	5
Gas Viscous Liquid Turbulent	tv	$Re_g<1000$ $Re_f>2000$	.046	16	.2	1	10
Liquid Viscous Gas Turbulent	vt	$Re_f<1000$ $Re_g>2000$	16	.046	1	.2	12
Gas Turbulent Liquid Turbulent	tt	$Re_f>2000$ $Re_g>2000$	.046	.046	.2	.2	20

Table 4.2

Martinelli-Nelson Local Multipliers used in HAMBO [10]

	Pressure (p.s.i.a.)								
Quality	14.7	100	500	1000	1500	2000	2500	3000	3206
0	1	1	1.0	1.0	1.0	1.00	1.00	1.00	1.00
0.05	30	15	5.3	3.6	2.4	1.75	1.43	1.17	1.00
0.10	69	28	8.9	5.4	3.4	2.45	1.75	1.30	1.00
0.20	150	56	16.2	8.6	5.1	3.25	2.19	1.51	1.00
0.30	245	85	23.0	11.6	6.8	4.04	2.62	1.68	1.00
0.40	350	115	29.2	14.4	8.4	4.82	3.02	1.83	1.00
0.50	450	145	34.9	17.0	9.9	5.59	3.38	1.97	1.00
0.60	545	174	40.0	19.4	11.1	6.34	3.70	2.10	1.00
0.70	625	199	44.6	21.4	12.1	7.05	3.96	2.23	1.00
0.80	685	216	48.6	22.9	12.8	7.70	4.15	2.35	1.00
0.90	720	210	48.0	22.3	13.0	7.95	4.20	2.38	1.00
1.00	525	130	30.0	15.0	8.6	5.90	3.70	2.15	1.00

Table 4.3

Slip Ratio Values Used By Thom [15]

P	$1/S \left(\frac{\rho_g}{\rho_f}\right)$
250	40.0
600	20.0
1250	9.80
2100	4.95
2000	2.15
3206	1

Table 4.4

Thom Void Fraction Correlation [1]

Steam Quality % By Wt.	Pressure (psia)				
	250	600	1250	2100	3000
	α	α	α	α	α
1	.288	.168	.090	.0476	.0213
5	.678	.512	.340	.207	.102
10	.816	.690	.521	.355	.193
20	.910	.833	.710	.553	.350
30	.945	.895	.808	.679	.480
40	.964	.930	.866	.767	.589
50	.975	.952	.908	.832	.682
60	.984	.967	.936	.881	.763
70	.990	.979	.959	.920	.834
80	.994	.988	.976	.952	.895
90	.997	.995	.989	.978	.951
100	1.	1.	1.	1.	1.

Table 4.5

Values of ϕ^2_{fo} for the Separated Flow Model as given by Thom [15]

Steam Quality % By Wt.	Pressure (psia)				
	250	600	1250	2100	3000
	ϕ^2_{fo}	ϕ^2_{fo}	ϕ^2_{fo}	ϕ^2_{fo}	ϕ^2_{fo}
1	2.12	1.46	1.10	-	-
5	6.29	2.86	1.62	1.21	1.02
10	11.1	4.78	2.39	1.48	1.08
20	20.6	8.42	3.77	2.02	1.24
30	30.2	12.1	5.17	2.57	1.40
40	39.8	15.8	6.59	3.12	1.57
50	49.4	19.5	8.03	3.69	1.73
60	59.1	23.2	9.49	4.27	1.88
70	68.8	26.9	10.19	4.86	2.03
80	78.7	30.7	12.4	5.45	2.18
90	88.6	34.5	13.8	6.05	2.33
100	98.86	38.30	15.33	6.664	2.480

Table 4.6

Baroczy Correlation Co-ordinates of Two-Phase Frictional Multiplier ϕ_{fo}^2 for G=1X10^{6}lb/hr ft^2 [16]

Physical Property Index $\frac{\left(\frac{\mu_f}{\mu_g}\right)^{0.2}}{\frac{\rho_f}{\rho_g}}$	Vapor Quality % by wt.														
	0.1	0.5	1	2	3.5	5	7.5	10	15	20	30	40	60	80	100
0.001	2.20	5.80	9.20	16.0	26.5	47.0	99.0	163	376	630	1,300	2,050	4,300	6,600	10,000
0.001	2.15	5.60	8.80	14.8	22.8	34.2	48.2	70.0	108	148	240	330	538	760	1,000
0.004	2.08	4.90	7.80	11.9	16.3	22.8	29.0	36.0	49.5	63.0	86.0	110	155	203	250
0.01	1.59	3.30	4.80	7.00	9.60	12.4	16.0	20.0	27.0	33.5	43.5	53.0	69.0	85.0	100
0.03	1.12	1.55	1.81	2.57	3.45	4.7	6.10	7.90	11.0	13.2	17.3	21.2	26.0	30.0	33.3
0.1	1.04	1.12	1.22	1.48	1.78	2.05	2.50	2.80	3.60	4.20	5.50	6.50	8.00	9.10	10.0
0.3	1.01	1.02	1.06	1.13	1.26	1.36	1.50	1.59	1.77	1.93	2.25	2.48	2.86	3.20	3.33
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 4.7

Values of B for Equation (4.66)

Γ	$G(\mathrm{lbm/hr\text{-}ft}^2)$	B
≤ 9.5	$\leq 3.69\text{X}10^5$	4.8
	$3.69\text{X}10^5 < G < 1.4\text{X}10^6$	$1.77\text{X}10^6/G$
	$\geq 1.4\text{X}10^6$	$1494/G^{.5}$
$9.5 < \Gamma < 28$	$\leq 4.426\text{X}10^5$	$14123/\Gamma G^{.5}$
	$\leq 4.426\text{X}10^5$	$21/\Gamma$
≥ 28	-	$4.075\text{X}10^5/\Gamma^2 G^{.5}$

Table 4.8

Constants for Equation (4.67)

Geometry	K	n
Round Tubes	.83(.087)	1.4
Rod Bundles and Annuli	.213(.0354)	1.6

Two values of K are given. The values in parentheses are for use if the variables of equation (4.67) are in CGS units and the others are for use with SI units. n is independent of the unit system.

Table 4.9

A Summary of Two-Phase Correlations

Correlation or Model	Ref.	Method of Application	Supporting Data	Models Used in Development and/or Application	
				Friction Factor (2)	Void Fraction
Armand	4	Eqn. 4.9	Air-water 15 psia	$f = .079/Re^{.25}$	SAME
Lockhart-Martinelli	5	Fig. 4.1	Air-various liquids 15-50 psia	$f = .046/Re^{.2}$	SAME
Martinelli-Nelson	6	Fig. 4.2	Steam-water 15-3000 psia	$f = .079/Re^{.25}$	SAME
Armand-Treschev	9	Eqn. 4.31	Steam-water 150-2700 psia	?	SAME
Levy Momentum Exchange	12	Eqn. 4.44	Steam-water 60-1400 psia	?	SAME
Martinelli-Nelson-Jones	11	Eqn. 4.45	?	Rough Tube	?
Bankoff	13	Eqn. 4.56	Steam-water 1000 psi	?	SAME
Sze-Foo Chien & Ibele	14	Eqn. 4.57	Air-water Near 15 psia	?	?
Thom	15	Tab. 4.5	Steam-water 15-3000 psia	Rough Tube	SAME
Baroczy	16	Fig. 4.5	Steam 139-2000 psia	$f = .046/Re^{.2}$	?

Table 4.9 (continued)

Correlation or Model	Ref.	Method of Application	Supporting Data (1)	Models Used in Development and/or Application	
				Friction Factor (2)	Void Fraction
Becker	17	Eqn. 4.61	Steam-water 100-600 psia	Rough Tube	Martinelli-Nelson
Borishansky	18	Eqn. 4.63	Steam-water 15-500 psia	$f = {}^{.046}/_{Re^{.2}}$	?
Chisholm (1973)	19	Eqn. 4.66	Other Correlations	?	?
C.I.S.E.	20	Eqn. 4.67	Steam-water 200-1500 psia	?	Homogeneous

NOTES

1. If steam-water data is used only that is indicated.
2. These friction factors are deduced from their being used in derivations, examples, or direct statements by the correlators.

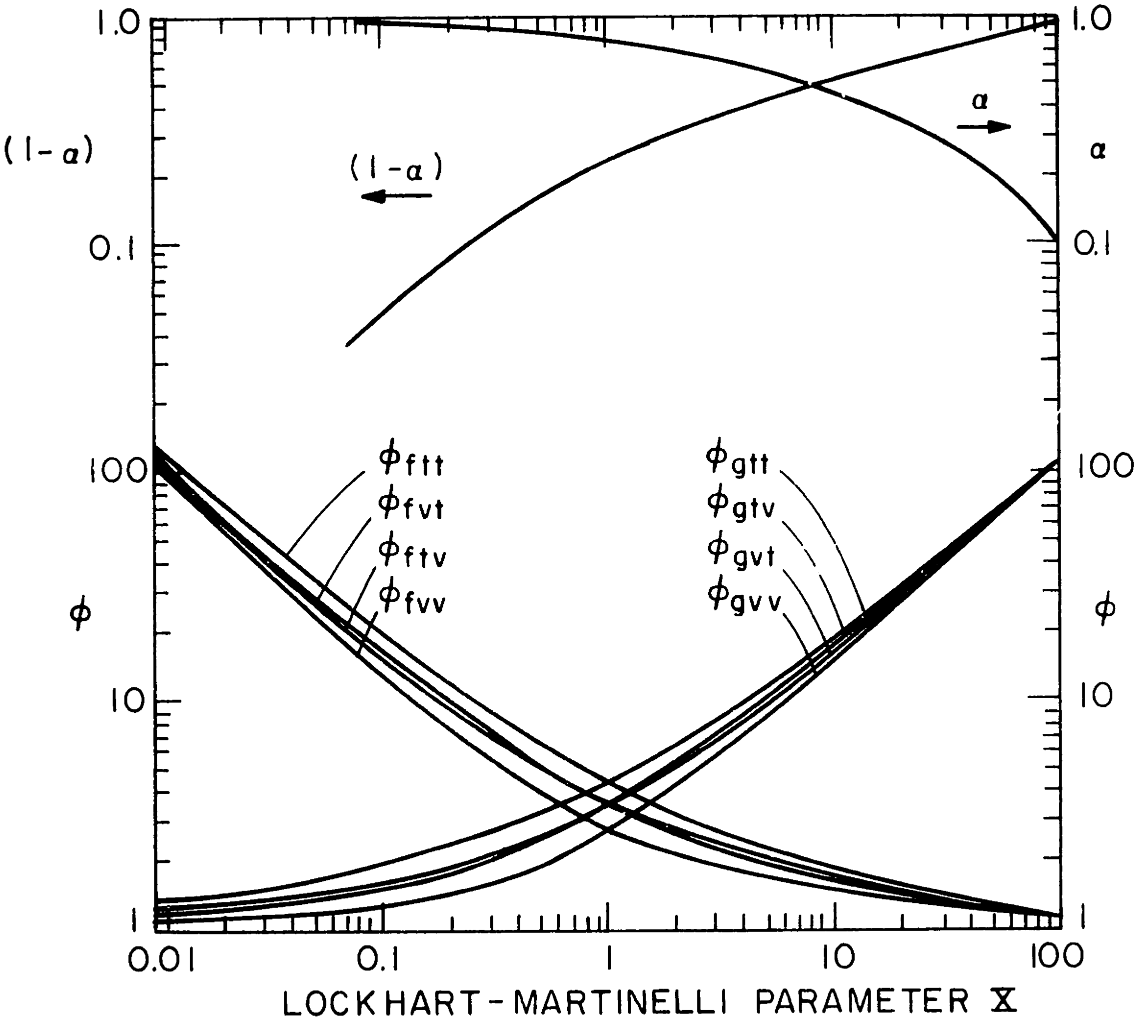


Figure 4.1 Lockhart - Martinelli Correlation [1]

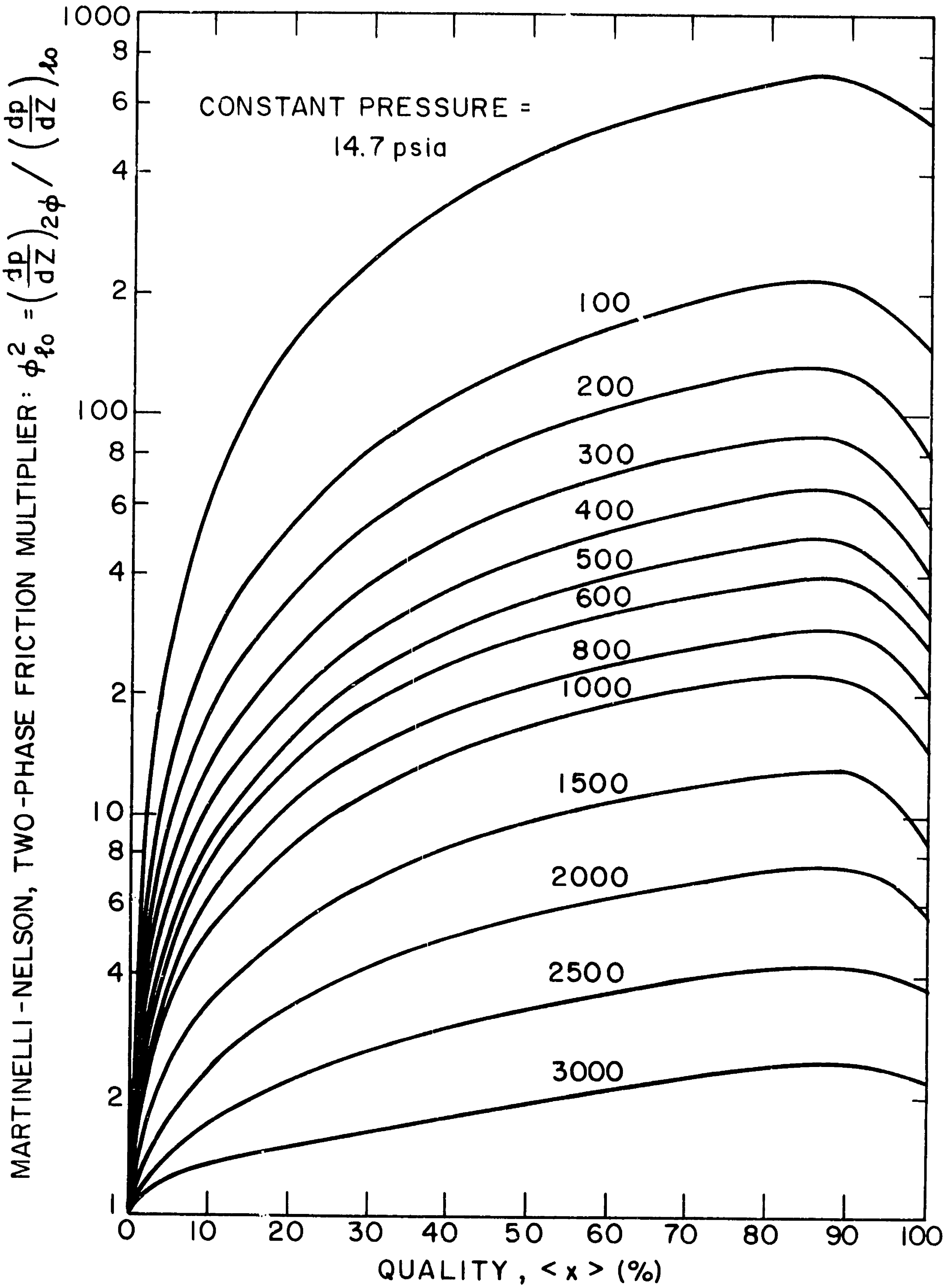


Figure 4.2 Martinelli - Nelson, Two-Phase Friction Multiplier for Steam/Water as a Function of Quality and Pressure [25]

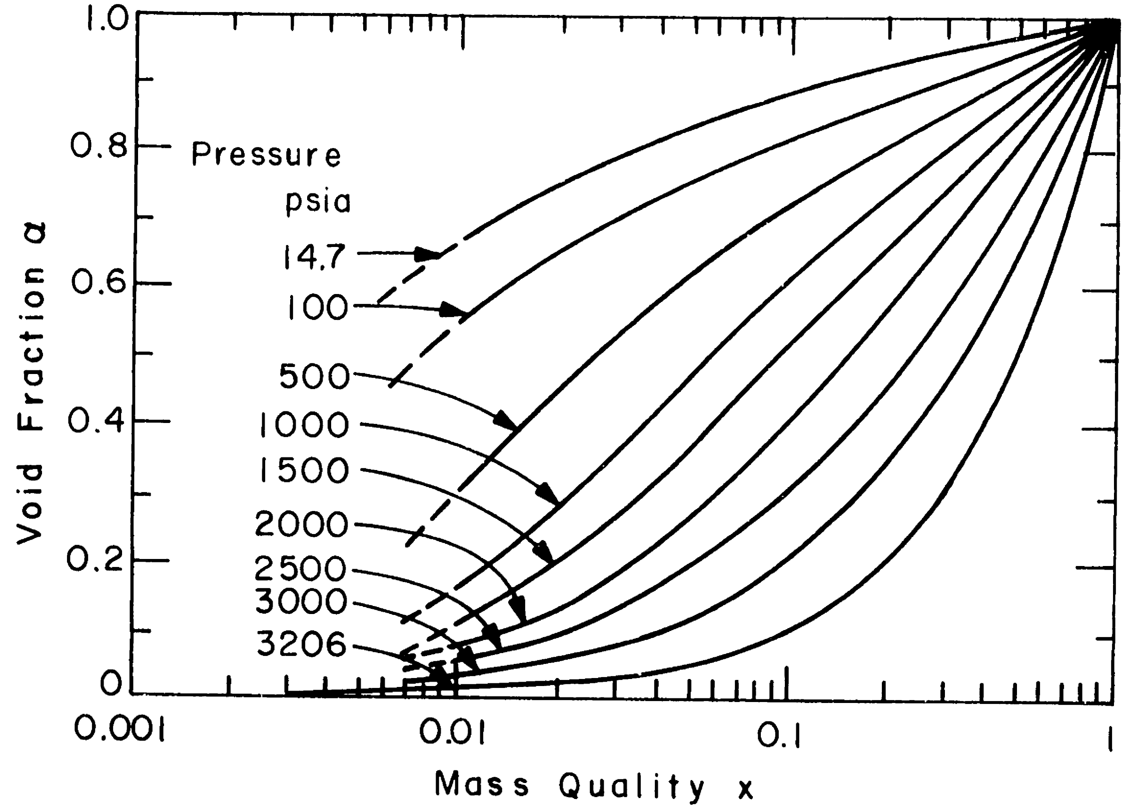


Figure 4.3 THE MARTINELLI-NELSON FRICTION PRESSURE DROP CORRELATION [6]

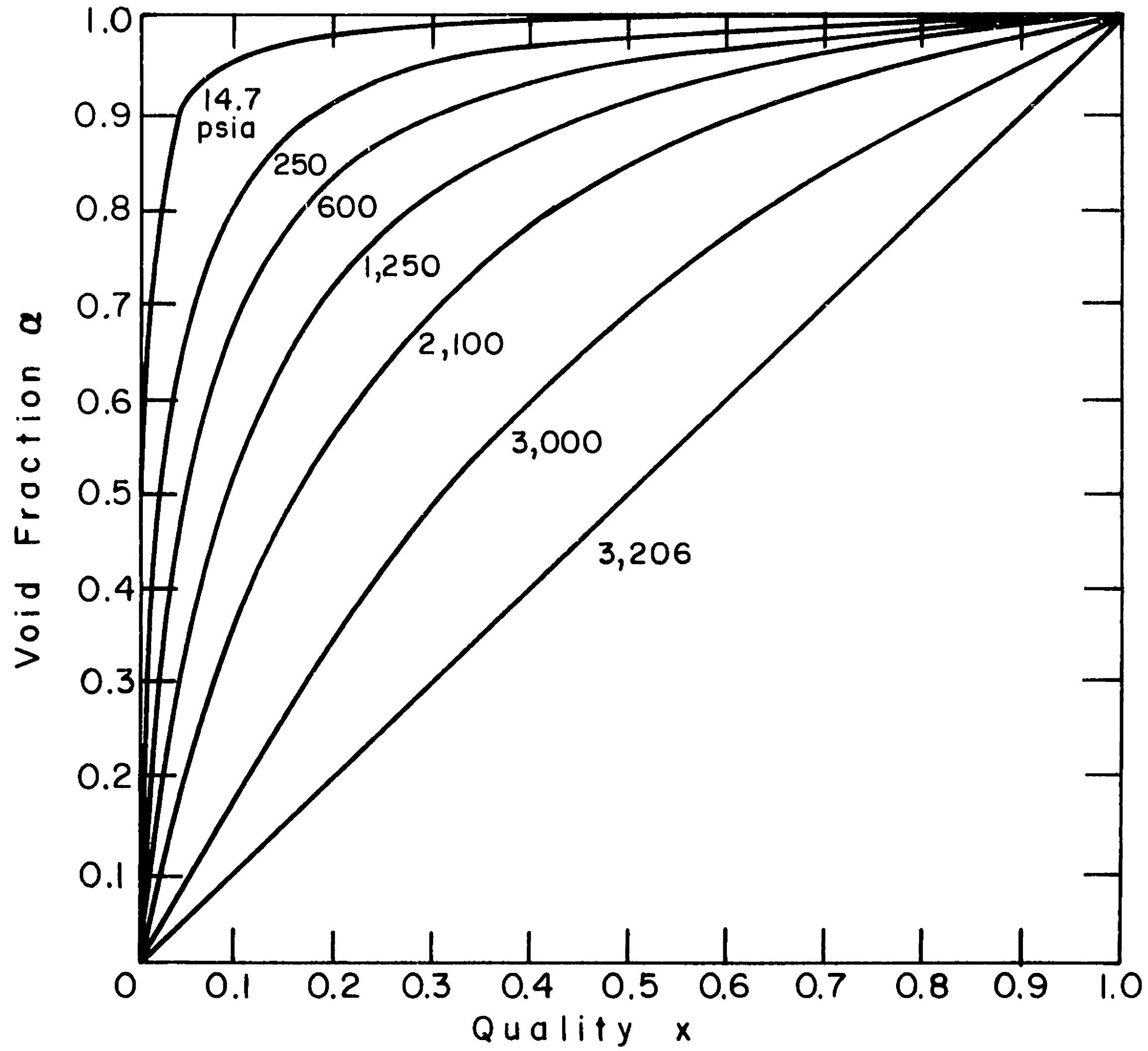


FIGURE 4.4 THOM VOID FRACTION CORRELATION [15]

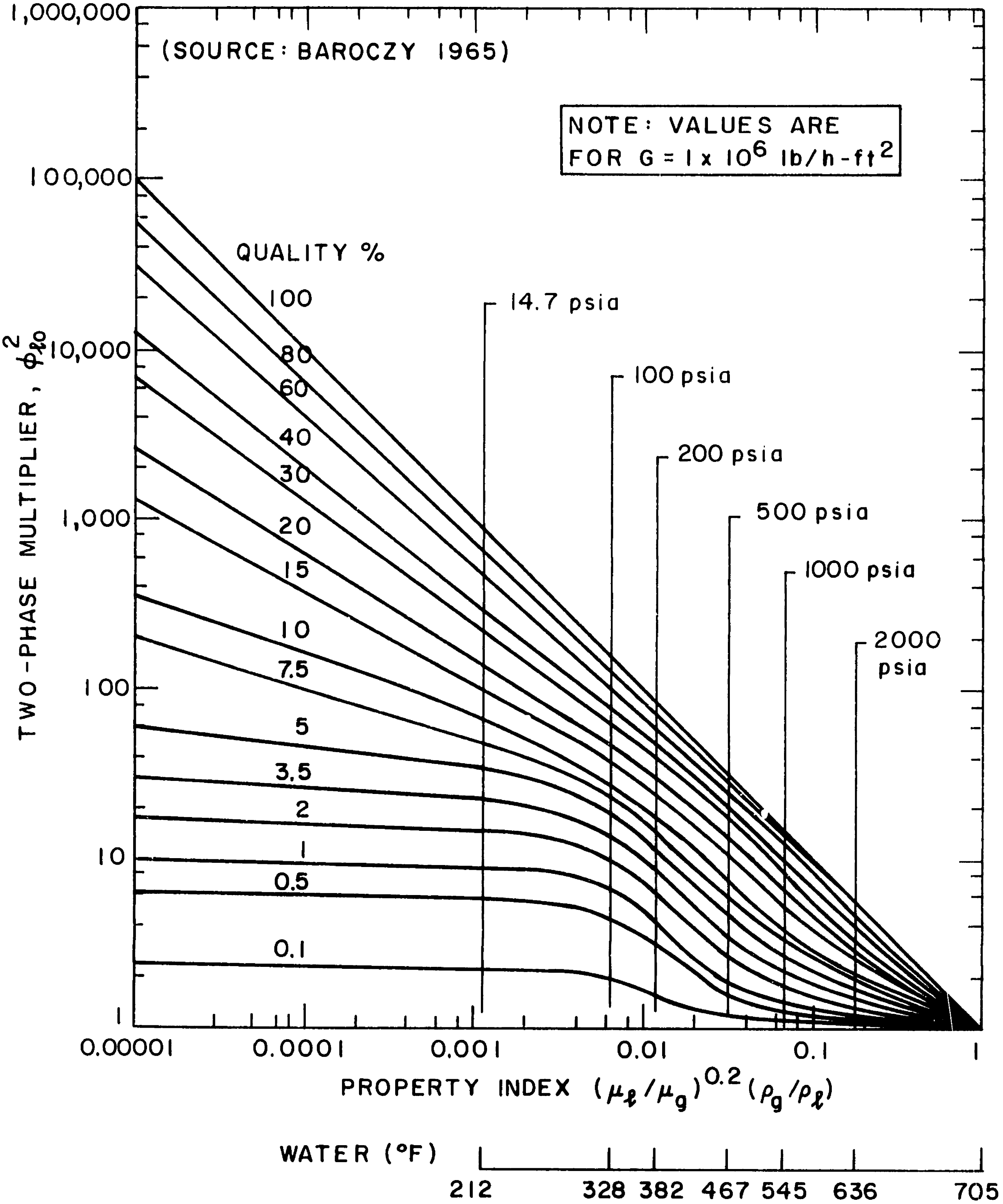


Figure 4.5 Baroczy's Two-Phase Friction Pressure Drop Correlation [25]

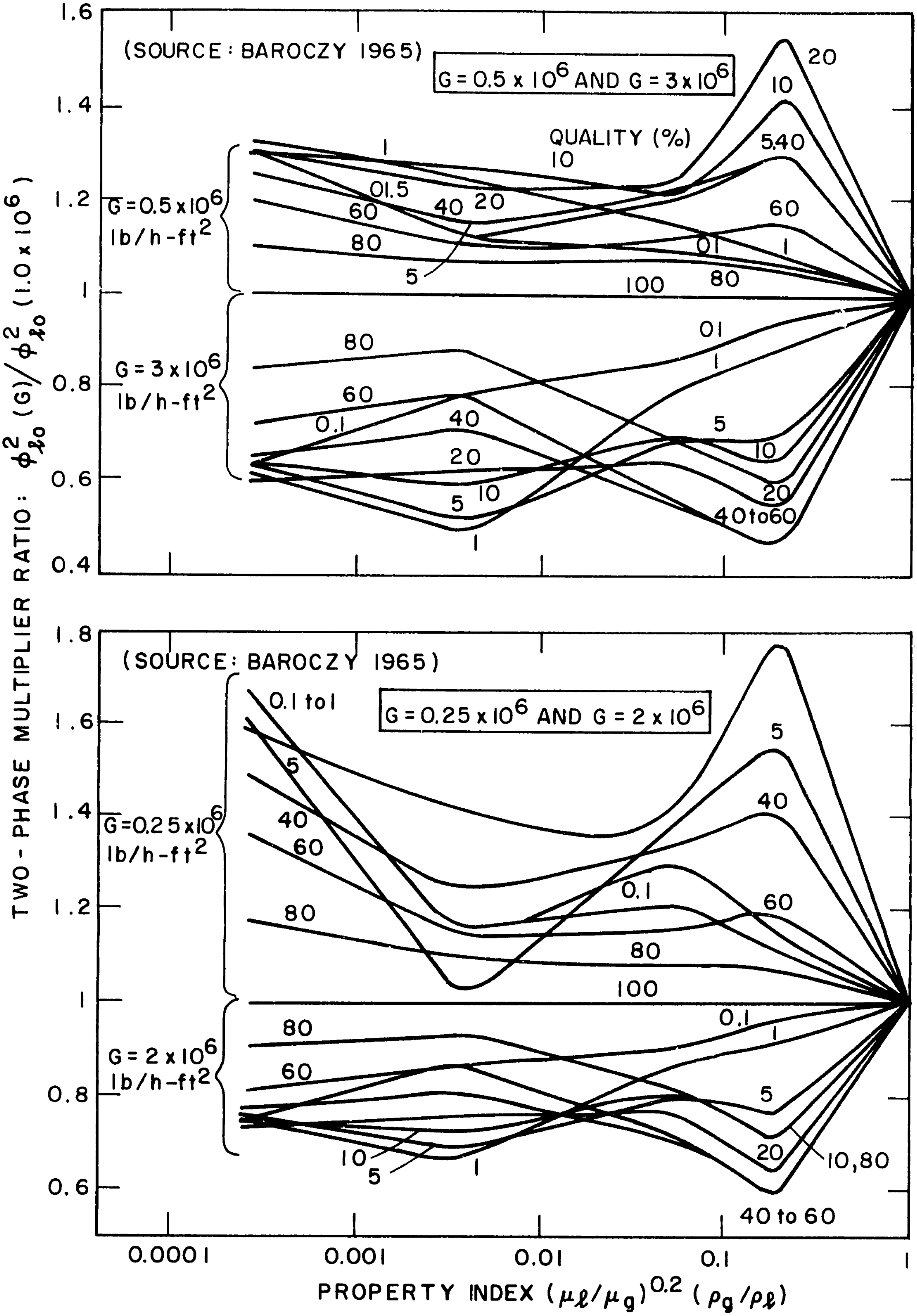


Figure 4.6 Mass Flux Correction Versus Property Index [25]

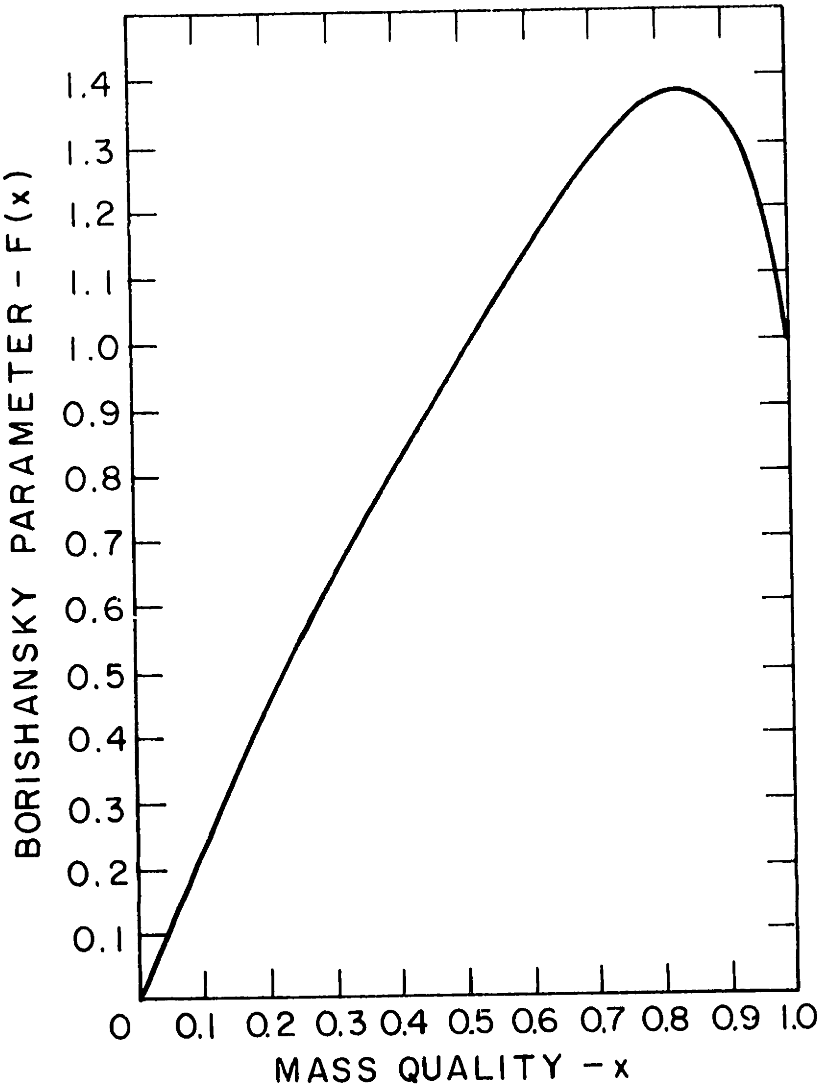


Figure 4.7 Borishansky Correlation [18]

Chapter 5

THE METHOD OF EVALUATION OF PRESSURE DROP CORRELATIONS

5.1 General

The correlations reviewed in the previous chapter were assessed by comparing the correlation two-phase friction multiplier to that derived from data. A difference ratio

$$\varepsilon = \frac{\left(\phi_{fo}^2\right) \text{correlation} - \left(\phi_{fo}^2\right) \text{data}}{\left(\phi_{fo}^2\right) \text{data}} \tag{5.1}$$

was used to quantify the discrepancy between the correlation and the data. A similar ratio of the quality - averaged friction multipliers was used for diabatic data. The calculation of the terms of equation (5.1) is discussed in subsequent sections.

Overall measures of merit of the correlations can be expressed as means, root-mean-square values or standard deviations of ε as given in equation (5.1) for all data points. The minimum root-mean-square value of ε for all data points is the primary figure of merit since it embodies the significance of both the mean error and the standard deviations. It is given as,

$$\varepsilon_{RMS} = \frac{\sum_{i=1}^{N} \varepsilon_i}{N} . \tag{5.2}$$

The mean and the standard deviation of all the values of are also presented. These same measures are used to assess data grouped in subsets of common physical properties. An uncertainty interval or range of possible error is calculated for each point as prescribed by Kline and McClintock [26]. The R.M.S. and mean uncertainty ranges were computed for various data sets Appendix A gives more details on the uncertainty analysis.

Approximately 2,200 adiabatic data points were used in this evaluation. An overall merit was established using this data and it was verified against approximately 1200 diabatic data points. The adiabatic data was also grouped by similar physical properties and compared with the correlations to determine the impact of mass velocity, pressure and quality on the suitability of the correlations.

5.2 Pressure Drop Data

The data used in this evaluation are identified in table 5.1. A primary objective was to use raw data so that common void correlations and friction factors could be employed in the manipulation of all data. It was also desirable to know the uncertainty in the two-phase friction multiplier derived from data.

The adiabatic and diabatic data used ranges in pressure from 200 to 1500 psia and covers the entire quality range and a large spectrum of mass velocities and configurations. This data specifies the measured pressure drop or gradient, the flow conditions and geometry. Most data sets provide adequate uncertainty information for the measured variables. These error intervals are given in table 5.2. Some data is presented without the uncertainty range. A median value of the error interval for other experiments as is given in table 5.2 is applied to these points.

There is a large amount of steam-water pressure drop data which has been presented in the literature in a graphical manner. For this sort of data the uncertainty information is often not presented. Then there is also the uncertainty in converting the plotted data to numerical quantities. Consequently, such data is not considered. Another limitation in the amount of data used is a function of the human resources in this effort. Consequently, adiabatic steam-water data at pressures less than 250 psia which is available was not used. The diabatic data is also limited to provide points covering a variety of geometries over the same range of conditions as that of the adiabatic data.

5.3 The Reduction of Pressure Drop Data

As stated earlier the pressure drop data was reduced to the two-phase multiplier, ϕ_{fo}^2, as defined by equation (2.18). Equation (3.14) was used to reduce the pressure drop to a friction pressure gradient. In the case of adiabatic data it was used as given. For diabatic data it was integrated in ten steps over the quality difference. In this case an average two-phase friction factor was calculated. It can be defined as

$$\frac{1}{X_{out}-X_{in}}\int_{X_{in}}^{X_{ont}} \phi_{fo}^{2}\, dx = \frac{\int_{o}^{z} \left(\frac{dP}{dz}\, F\right) dz}{\int_{o}^{z} \left(\frac{dP}{dz}\, F\right)_{fo} dz}. \tag{5.3}$$

The adiabatic raw data was reduced by several methods. Three methods of calculating the void fraction were used, the Thom correlation, the homogeneous model and the Martinelli-Nelson correlation. The Thom correlation was selected as the primary void fraction because of its reputed steam-water data base. The Martinelli-Nelson void fraction correlation and the slip ratio of unity (homogeneous model) were used to determine the effects of the different void fraction models on the results. The homogeneous void fraction model was used to provide data reduced by the same method as that on which the CISE correlation was. It also provides for a completely homogeneous computation of data based multipliers for comparison with those homogeneous model friction multipliers given in equations (3.6) and (3.11) through (3.13).

The effects of the friction factors were also examined. The adiabatic data was reduced using both approximations (equations (2.26) and (2.27)) and the smooth tube friction factor given by equation (2.28). The diabatic data was reduced to an average multiplier using only the smooth tube friction factor and the Thom void fraction correlations.

Much of the diabatic data was for flows having subcooled inlet conditions. The location of the point of zero quality was determined using equilibrium thermodynamics. The region from the inlet to this point the flow was treated as a single-phase flow with a friction factor of .0075 being used for the rod bundle data presented Lahey et al [35], which is consistent with their single-phase experimental results, and .005 for other ducts.

The computer programs used to reduce data are discussed and listed in detail in Appendix B. The output of these programs were the input to an evaluation program. This output described the geometry of the duct and the flow conditions as well as giving the friction multiplier base on the data and its uncertainty range.

5.4 The Evaluation of the Correlations

For each data point the computer program assessing the correlations computed two phase friction multipliers for each of the correlations given in Chapter 4, as well as the four homogeneous two-phase multiplier given in Chapter 3. These multipliers were compared with experimental result using equation (5.1) and the appropriate mean differences, R.M.S. differences and standard deviations were computed.

This output was given for each data set as well as the entire data collection. Each set of reduced adiabatic data was evaluated twice, once as sets based on the source of data and secondly as groupings of like properties. The property groupings combined data of similar pressure ranges, quality ranges and mass velocity ranges. The intention behind these groupings was to determine the flow conditions at which a correlation may be most or, for that matter, least effective. Table 5.3 gives the property ranges that were used. They were selected so as to provide a significant number of points in each data grouping. In all, 42 subsets, each having a specific pressure, mass velocity and quality range were formed by mechnically sorting the output of the data.

For diabatic data the correlation multipliers were determined and averaged over the quality range of the data point. The average multipliers based on the correlation were compared with the data average multiplier in the same manner as the adiabatic data. Appendix C provides further details on the programming of the correlations and a listing of the program.

Table 5.1

Data Used in This Study

Data Set (Note 1)	Ref.	Points	Configuration	Flow Direction	De (in)	Pressure Range (psia)	Mass Velocity Range $\frac{(\text{lbm/hr-ft}^2)}{10^6}$	Quality Range	Mean Data Uncertainty	RMS Data Uncertainty
A-1	28	54	Rd. Tube	Up	.205	990-1010	.8-2.9	.05-.63	.059	.060
A-2	28	172	Rd. Tube	Up	.205	580-1210	.7-2.9	.01-.71	.063	.068
A-3	28	49	Rd. Tube	Up	.197	990-1010	.7-3.3	.01-.64	.063	.065
A-4	28	58	Rd. Tube	Up	.205	990-1020	.7-3.0	.02-.73	.059	.060
A-5	28	74	Rd. Tube	Up	.248	990-1020	.7-3.0	.03-.85	.061	.063
A-6	28	57	Rd. Tube	Up	.323	990-1010	.7-3.0	.15-.65	.059	.059
A-7	28	27	Rd. Tube	Up	.398	990-1020	.8-2.4	.03-.75	.069	.075
A-8	28	61	Annulus	Up	.197	990-1040	.8-2.6	.04-.76	.060	.061
A-9	28	68	Annulus	Up	.276	990-1030	.8-3.4	.01-.72	.067	.075
A-10	28	151	Annulus	Up	.127	990-1030	.7-2.9	.00-.74	.062	.066
A-11	29	51	Rd. Pipe	Up	.318	1010-1020	.8-2.9	.03-.90	.060	.061
A-12	29	72	Rd. Pipe	Up	.193	710-1300	.8-2.9	.01-.60	.060	.061
A-13	29	360	Rd. Pipe	Up	.361	730-1030	.3-2.9	.02-1.0	.066	.072
A-14	29	42	Rd. Pipe	Up	.598	730- 740	.7-1.1	.25-.98	.057	.057
A-15	29	268	Rd. Pipe	Up	.598	280-1310	.3-1.5	.02-.98	.122	.444
A-16	29	155	Rd. Pipe	Up	.200	1000-1030	.7-2.9	.02-.96	.050	.061
A-17	29	66	Rd. Pipe	Up	.197	990-1030	.8-2.9	.03-.81	.059	.059
A-18	29	13	Rd. Pipe	Up	.198	1010-1030	.8-1.2	.07-.87	.058	.058
A-19	29	26	Rd. Pipe	Up	.197	1000-1020	1.1-2.9	.02-.87	.056	.056
A-20	29	37	Annulus	Up	.098	730-1180	.5-2.9	.01-.51	.053	.053
A-21	31	23	Annulus	Up	.194	1010-1040	.5-2.3	.01-.52	.081	.094
A-22	31	22	Annulus	Up	.194	1010-1040	.8-2.9	.00-.53	.151	.221
A-23	30	43	Rect. Channel	Up	.778	600-1410	.5-2.1	.02-.99	.166	.225
A-24	30	26	Rect. Channel	Down	.778	600-1010	.2-2.1	.02-.79	.131	.149
A-25	30	62	Rect. Channel	Horiz.	.778	600-1420	.2-2.1	.02-.77	.061	.061

Table 5.1 (continued)

Date Set (Note 1)	Ref.	Points	Configuration	Flow Direction	De (in)	Pressure Range (psia)	Mass Velocity Range $\frac{(\text{lbm/hr-ft}^2)}{10^6}$	Quality Range	Mean Data Uncertainty	RMS Data Uncertainty
A-26	30	23	Rect. Channel	Up	.438	600-1410	.5-2.1	.05-.92	.064	.064
A-27	30	18	Rect. Channel	Horiz.	.438	600-1010	.5-2.1	.05-.90	.062	.062
A-28	30	36	Rd. Pipe	Up	.955	600-1400	.2-1.1	.09-.90	.099	.121
A-29	30	44	Rd. Pipe	Horiz.	.955	600-1400	.2-1.1	.09-.90	.062	.062
A-30	30	14	Rd. Pipe	Horiz.	1.27	1000	.2- .6	.09-.90	.062	.062
A-31	30	14	Rd. Pipe	Horiz.	.742	1000	.8-1.7	.09-.90	.062	.062
A-32	30	37	Rd. Pipe	Down	.742	600-1400	.2-1.1	.09-.90	.045	.104
A-33	32	6	Rd. Pipe	Up	.683	980-1030	1.-1.6	.05-.25	.150	.183
D-1	29	15	Rd. Pipe	Up	.198	980-1030	.7-1.2	-.17-.71	.133	.148
D-2	29	121	Rd. Pipe	Up	.199	720-1300	.7-2.9	-.31-.96	.073	.077
D-3	29	70	Rd. Pipe	Up	.200	1000-1030	.7-2.8	-.06-.98	.064	.065
D-4	29	159	Rd. Pipe	Up	.197	720-1300	.8-2.9	-.14-.99	.075	.077
D-5	29	270	Rd. Pipe	Up	.197	1000-1040	.8-3.0	-.13-.91	.068	.070
D-6	29	71	Rd. Pipe	Up	.197	990-1050	.8-3.0	-.12-.86	.080	.082
D-7	28	309	Rd. Pipe	Up	.205	590-1600	.7-2.9	-.06-.83	.088	.090
D-8	28	143	Rd. Pipe	Up	.205	995-1020	.8-2.9	.01-.84	.071	.072
D-9	22	12	Annulus	Up	.270	1000	1.-2.6	.06-.74	.102	.105
D-10	32	5	Rd. Pipe	Up	.683	993-1005	1.-1.6	0.0-.30	1.46	1.46
D-11	35	31	Array	Up	.474	1000	.2-2.2	-.81-.45	.748	1.15
D-12	38	25	Rect. Channel	Up	.333	1200	.3-.5	-.06-.65	1.42	1.42

Note 1: A - Adiabatic, D - Diabatic.

Table 5.2

Uncertainty Intervals for Measured Variables

Property	Uncertainty Intervals						Median
Static Pressure (P)	10 psi	5 psi	10 psi	5 psi		15 psi	10 psi
Pressure Drop (ΔP)	2.5%	2.5%	.04 psi	1.2%	.01 psi	2.5%	2.5%
Mass Flow Rate (W)	1%	.6%	2%	2%	1%	1%	1%
Diameters (D)	1%	1%	1%	1%			1%
Power to Boiler (Φ_1)	3%	2%	1%	3%		2%	2%
Power to Test Section(Φ_2)	2%	1%	1%		2%	1%	1%
Inlet Termperatures (T_{in})	4°F	2°F	5°F	4°F	2°F	4°F	4°F
Notes		2	1,7	4		3,5,6	
Reference	28,37	29,36	32	30	38	31	Used on Data of 35,38,22

NOTES

1) The boiler is a heated length before test section pressure taps and is part of the same circuitry as the test section.

2) The boiler power uncertainty varied depending on measuring equipment attached between 1 to 2.2 percent.

3) The boiler power uncertainty calculated knowing a quality uncertainty of .02 at $x = 0$.

4) The pressure drop accuracy reported to be .3 percent of full scale of three manometers with liquids of different densities. The uncertainty is estimated based on manometer reading at ¼ length.

NOTES (continued)

5) The pressure drop error is based on 1 percent of full scale for 2000mm mercury manometer.

6) The reference (31) pressure drop uncertainty can be much higher than 2.5%.

7) The pressure drop uncertainty based on accuracy of static pressure profile accuracy of .02 psi over test section.

Table 5.3

The Ranges of Physical Properties Used to Form Data Subsets for Evaluation by Properties

PRESSURE:	$P < 900$ psia, $P > 900$ psia,
MASS VELOCITY:	$G < 1\text{x}10^6 \text{lbm/hr-ft}^2$, $1\text{x}10^6 \leq G < 2\text{x}10^6 \text{lbm/hr-ft}^2$ $G \geq 2\text{x}10^6 \text{lbm/hr-ft}^2$.
QUALITY:	$0 \leq x < .1$, $.1 \leq x < .2$, $.2 \leq x < .3$, $.3 \leq x < .4$, $.4 \leq x < .5$, $.5 \leq x < .7$, $.7 \leq x < 1.0$.

42 data subsets were formed.

Chapter 6

RESULTS OF THE EVALUATION

6.1 Adiabatic Data

The comparison of data to correlations and models reveals that there is considerable difference between them. It is the purpose of this study to evaluate these correlations to determine which of them coincide most nearly with data.

Tables 6.2 through 6.6 give the overall evaluation of adiabatic data. These five tables give the mean, the root-mean-square and the standard deviation of the discrepancy, ε, for all of the adiabatic data. The data in each table has been reduced using different friction factors and void fraction models and correlations as is indicated. The correlations are identified by numbers which matched with the appropriate names in Table 6.1. The terms data error and correlation error appearing in these tables refer to the uncertainty in the friction multiplier based on data and the discrepancy between data and correlations, respectively.

A quick survey of these tables indicates that there is a large range of discrepancies between the data and the correlations. It is noted that the three correlations based on data at pressures near one atmosphere relate to the data very poorly. The Lockhart-Martinelli, Armand, and Sze-Foo

Chien-Ibele correlations display the greatest difference with data.

The correlations and models which exhibited the minimum discrepancies had R.M.S. correlation errors substantially larger than the RMS data uncertainty. There is obviously no perfect correlation. None are based on all the data that exists. The correlations are, thus, strongly dependent on the data used by the correlator. There must then be some limitation on the range of applicability of any correlation. In effect there is some degree of uncertainty associated with it. So therefore, it is not unreasonable that the best correlations' values of the R.M.S. differences range from .25 to .30 while the data R.M.S. uncertainty ranges from about .08 to .17.

There are several models and correlations which have overall differences with the data very near to that of the correlation having the least discrepancy. Table 6.7 gives the correlations which had R.M.S. differences with less than 0.1 of the minimum in value. It is noted that, in general, the same correlations and models comprise this group regardless of how the data is reduced. The one exception is the improved characteristics of the Chisholm correlation when the homogeneous and Martinelli-Nelson void correlations are used in the reduction of data. The Chisholm correlation is just outside the arbitrary limit for the other methods of reducing data. The altering of the method of reducing data has only limited effect on the results. In most cases, including the Chisholm work, the difference in results by using the different models for void fraction and single phase pressure drop in data reduction is at best equal to the uncertainty in the data.

The CISE correlation RMS error decreases significantly when the homogeneous model is used to calculate the void fraction in reducing data. This coincides with the fact that the homogeneous model was used to develop that correlation. The CISE correlation may be strongly effected by the friction factor used. It is noted in section 4.15 that no friction factor is used in applying this correlation and none was needed to develop it. In this study the friction factor is used to calculate a liquid-only friction pressure drop which is then divided into the pressure drop determined by the correlation to convert it to a friction multiplier for comparison with data. This study is not a wholly valid evaluation of the CISE correlation since no friction factor is required for calculations as in other correlations and models.

Appendix D gives results for data grouped in their original sets as described by table 5.1 in a similar format. Appendix E gives the data grouped in collections having like physical properties. Table 6.8 indicates the property groupings for this data. The data set information is useful in noting the effectiveness of correlations for different geometries and flow orientations. The results of the property groups gives an indication of how the correlations behave in different ranges of pressure, mass velocity and quality.

6.2 Results of the Comparison of Diabatic Data

The overall results of the comparison with diabatic data is given in Table 6.9. The four correlations having the least discrepancy with the data are same as was the case for the diabatic data. There is some shifting of positions for some correlations, but in general the results coincide with that of the adiabatic data. There is greater uncertainty in the diabatic data, and expecially so if there is subcooling (see appendix A). This greater scatter is naturally reflected by the higher RMS discrepancies between correlation and data.

The evaluation of the difference between correlation and other data for each of the diabatic data sets which are listed and described in Table 5.1 are given in Appendix F.

6.3 Applicability of Results to Boiling Water Reactors

Boiling Water Reactors operate within the limits of the data used in this study. The data subsets in Appendix E that are pertinent to the normal operation of the BWR are those representing the following properties:

Pressure; 900-1500 psia

Mass Velocity; 0 - $1x10^6$ lbm/hr-ft^2, $1x10^6$ - $2x10^6$ lbm/hr-ft^2

Quality; 0-0.1, 0.1-0.2

These include the data sets numbered 4, 5, 10 and 11. The correlation which had the least RMS error overall for these four data sets is the Armand-Treschev correlation.

In the event of a reactor accident, such as the loss of coolant, the quality can be as high as 0.6. Under these circumstances data sets 16, 17, 22, 23, 28, and 29 are also applicable. The Armand-Treschev correlation performed best up to a quality of 0.3. At the higher qualities (sets 22, 23, 28, 29) the Baroczy correlation gave the best results.

A typical BWR 8 x 8 rod bundle has an equivalent diameter of .535 inches. A review of the data sets in Appendix D indicates that the Thom and Baroczy correlations perform the best in the sets having equivalent diameters near one half inch. Since the data sets of Appendix D are grouped by geometry and include regions of high velocites and qualities the property groupings are considered applicable. Therefore, the Armand-Treschev correlation is recommended for BWR pressure drop analysis at qualities of less than 0.3 and the Baroczy correlation for higher qualities.

Table 6.1

Two-Phase Friction Pressure Drop Correlation Identification

Correlation or Model	Number
Homogeneous, Equation (3.6)	1
Homogeneous, Equation (3.11)	2
Homogeneous, Equation (3.12)	3
Homogeneous, Equation (3.13)	4
Armand	5
Armand-Treschev	6
Lockhart-Martinelli	7
Martinelli-Nelson	8
Bankoff	9
Martinelli-Nelson-Jones	10
Levy Momentum Exchange	11
Sze-Foo Chien-Ibele	12
Thom	13
Baroczy	14
Becker	15
Borishansky	16
Chisholm	17
C.I.S.E.	18

```
DATA SETS   POINTS   DATA MN   DATA RMS   CORRELATION   CORRELATION   CORRELATION   CORRELATION
                      ERROR     ER  R                    MN   ERROR    RMS ERROR     STD    DEV

     33      2238   0.07382   0.16737
                                                1        -0.09166       0.28227       0.26698
                                                2        -0.26023       0.34628       0.22844
                                                3        -0.17506       0.30489       0.24963
                                                4        -0.33098       0.39019       0.20665
                                                5         1.13285       2.06501       1.72653
                                                6         0.02490       0.36431       0.36346
                                                7         1.45561       1.71476       0.90642
                                                8         0.47765       0.64754       0.43721
                                                9        -0.22882       0.53899       0.48801
                                               10         0.78742       0.92927       0.49347
                                               11         0.35920       0.83429       0.75300
                                               12         2.80295       3.40723       1.93719
                                               13        -0.09636       0.28234       0.26539
                                               14        -0.08812       0.30971       0.29691
                                               15         0.83546       1.00450       0.55770
                                               16         0.14530       0.37208       0.34254
                                               17         0.00525       0.40458       0.40455
                                               18         0.27622       0.48827       0.40262
```

Table 6.2

Overall Results For Adiabatic Data Reduced Using
The Thom Void Fraction Correlation And
The Single-Phase Friction Factor,
$f=.046/Re^{.2}$

DATA SETS	POINTS	DATA MN ERROR	DATA RMS ERR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
33	2220	0.07339	0.16777				
				1	-0.13747	0.28153	0.24568
				2	-0.29819	0.36498	0.21047
				3	-0.21723	0.31607	0.22959
				4	-0.36511	0.41191	0.19068
				5	1.02831	1.91258	1.61262
				6	-0.02687	0.34014	0.33907
				7	1.32518	1.56691	0.83613
				8	0.40187	0.56763	0.40086
				9	-0.27010	0.53252	0.45894
				10	0.69923	0.83848	0.46274
				11	0.29510	0.77447	0.71605
				12	2.60438	3.16457	1.79769
				13	-0.14188	0.28260	0.24440
				14	-0.13331	0.31166	0.28172
				15	0.74293	0.90297	0.51324
				16	0.08663	0.32585	0.31412
				17	-0.04310	0.39101	0.38862
				18	0.21607	0.44369	0.38753

Table 6.3

Overall Results For Adiabatic Data Reduced Using
The Thom Void Fraction Correlation And
The Single-Phase Friction Factor,
$f=.079/Re^{.25}$

DATA SETS	POINTS	DATA MN ERROR	DATA RMS ER R	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
33	2224	0.07436	0.17152				
				1	-0.09821	0.28310	0.26551
				2	-0.26584	0.34968	0.22716
				3	-0.18125	0.30741	0.24829
				4	-0.33597	0.39380	0.20543
				5	1.12506	2.05268	1.71689
				6	0.01695	0.36211	0.36171
				7	1.43465	1.69429	0.90133
				8	0.46637	0.63767	0.43488
				9	-0.23521	0.53995	0.48602
				10	0.77346	0.91599	0.49071
				11	0.35125	0.82707	0.74878
				12	2.77705	3.38061	1.92782
				13	-0.10287	0.28325	0.26391
				14	-0.09601	0.31031	0.29509
				15	0.82218	0.99191	0.55489
				16	0.13659	0.36718	0.34083
				17	-0.00323	0.40185	0.40184
				18	0.26630	0.48010	0.39948

Table 6.4

Overall Results For Adiabatic Data Reduced With
The Thom Void Friction Correlation And
The Smooth Tube Single-Phase
Friction Factor

DATA SETS	POINTS	DATA MN ERROR	DATA RMS ERR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
33	2230	0.06664	0.07776				
				1	-0.10213	0.26342	0.24281
				2	-0.27044	0.33370	0.19549
				3	-0.18548	0.28869	0.22121
				4	-0.34039	0.38263	0.17475
				5	1.13029	2.07565	1.74091
				6	0.01339	0.34722	0.34697
				7	1.42297	1.65884	0.85260
				8	0.45915	0.60414	0.39264
				9	-0.23855	0.53475	0.47859
				10	0.76443	0.86339	0.40135
				11	0.34826	0.82223	0.74483
				12	2.79383	3.40384	1.94437
				13	-0.10673	0.26179	0.23904
				14	-0.10102	0.26932	0.24966
				15	0.81754	0.97803	0.53681
				16	0.13235	0.34453	0.31809
				17	-0.00867	0.33676	0.33665
				18	0.25792	0.39548	0.29981

Table 6.5

Overall Results For Adiabatic Data Reduced With
Martinelli-Nelson Void Fraction Correlation
And Smooth Tube Single-Phase
Friction Factor

DATA SETS	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
33	2225	0.06674	0.07924				
				1	-0.12140	0.27350	0.24508
				2	-0.28672	0.34655	0.19465
				3	-0.20354	0.30022	0.22069
				4	-0.35476	0.39578	0.17547
				5	1.08978	2.02734	1.70953
				6	-0.00732	0.35009	0.35001
				7	1.36753	1.60397	0.83820
				8	0.42699	0.58035	0.39305
				9	-0.25941	0.52529	0.45677
				10	0.72090	0.81884	0.38834
				11	0.32460	0.81880	0.75171
				12	2.72105	3.34350	1.94291
				13	-0.12599	0.27228	0.24137
				14	-0.12581	0.26202	0.22984
				15	0.77948	0.95011	0.54325
				16	0.10741	0.33557	0.31791
				17	-0.03820	0.30830	0.30592
				18	0.22638	0.36695	0.28879

Table 6.6

Overall Results for Adiabatic Data Reduced With
The Homogeneous Void Fraction Model And
Smooth Tube Single-Phase Friction Factor

Table 6.7

Two-Phase Pressure Drop Correlations and Models Having the Least Discrepancy with The Entire Data Collection

Data Reduction Method						
Friction Factor		$f=.046/Re^{.2}$	$f=.079/Re^{.25}$	Smooth Tube	Smooth Tube	Smooth Tube
Void Fraction		Thom	Thom	Thom	Martinelli Nelson	Homogeneous Model
RANKING	1	Homogeneous Eqn. (3.6)	Homogeneous Eqn. (3.6)	Homogeneous Eqn. (3.6)	Thom	Baroczy
	2	Thom	Thom	Thom	Homogeneous Eqn. (3.6)	Thom
	3	Homogeneous Eqn. (3.12)	Baroczy	Homogeneous Eqn. (3.12)	Baroczy	Homogeneous Eqn. (3.6)
	4	Baroczy	Homogeneous Eqn. (3.12)	Baroczy	Homogeneous Eqn. (3.12)	Homogeneous Eqn. (3.12)
	5	Homogeneous Eqn. (3.11	Borishansky	Homogeneous Eqn. (3.11)	Homogeneous Eqn. (3.11)	Chisholm
	6	Armand-Treschev	Armand-Treschev	Armand-Treschev	Chisholm	Homogeneous Eqn. (3.11)
	7	Borishansky	Homogeneous Eqn. (3.11)	Borishansky	Borishansky	Armand-Treschev
	8	-----------	-----------	-----------	Armand-Treschev	-----------

Correlations having ε_{RMS} within 0.1 of the minimum.

Table 6.8

The Adiabatic Data Subsets Based On Physical Properties

Pressure (psia)	Mass Velocity $\frac{lbm/hr\text{-}ft^2}{10^6}$	Mass Quality	Points	Data Set Number In Appendix E
250-900	0-1	0-.1	20	1
		.1-.2	42	7
		.2-.3	29	13
		.3-.4	34	19
		.4-.5	28	25
		.5-.7	53	31
		.7-1.	48	37
	1-2	0-.1	30	2
		.1-.2	37	8
		.2-.3	28	14
		.3-.4	31	20
		.4-.5	17	26
		.5-.7	23	32
		.7-1.	17	38
	2-3	0-.1	13	3
		.1-.2	8	9
		.2-.3	9	15
		.3-.4	9	21
		.4-.5	9	27
		.5-.7	9	33
900-1500	0-1	0-.1	67	4
		.1-.2	86	10
		.2-.3	79	16
		.3-.4	68	22
		.4-.5	54	28
		.5-.7	110	34
		.7-1.	94	39
	1-2	0-.1	107	5
		.1-.2	143	11
		.2-.3	95	17
		.3-.4	90	23
		.4-.5	77	29
		.5-.7	129	35
		.7-1.	63	40

Table 6.8 (continuted)

Pressure (psia)	Mass Velocity $\frac{\text{lbm/hr-ft}^2}{10^6}$	Mass Quality	Points	Data Set Number in Appendix
900-1500	2-3	0-.1	84	6
		.1-.2	90	12
		.2-.3	76	18
		.3-.4	63	24
		.4-.5	57	30
		.5-.7	69	36
		.7-1.	27	41

DATA SETS	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATI STD DE
12	1231	0.12672	0.29829				
				1	-0.05580	0.42844	0.42479
				2	-0.25223	0.40751	0.32007
				3	-0.15497	0.39565	0.36404
				4	-0.31868	0.43580	0.29726
				5	1.12192	1.93829	1.58059
				6	0.07791	0.55912	0.55367
				7	1.55363	1.92893	1.14325
				8	0.52776	0.83960	0.65299
				9	-0.30963	0.45589	0.33460
				10	0.71956	0.99074	0.68103
				11	0.47312	1.04566	0.93250
				12	3.44567	4.29905	2.57084
				13	-0.06358	0.42290	0.41810
				14	-0.19803	0.37259	0.31560
				15	0.96854	1.33337	0.91641
				16	0.19576	0.55865	0.52322
				17	-0.10241	0.48535	0.47443
				18	0.12781	0.44274	0.42389

Table 6.9

Overall Results for Diabatic Data Reduced with
The Thom Void Fraction Correlation
And Single-Phase Smooth Tube
Friction Factor

Chapter 7

CONCLUSIONS

In reviewing correlations it is seen that several of them are based on only small amounts of steam-water pressure drop data or data limited to certain flow conditions. It is not expected that these correlations would be very applicable for conditions extremely different from those upon which they are based. The Lockhart-Martinelli, Armand and Sze-Foo Chien and Ibele correlations are all based on very low pressure data, none of which was for steam and water. The Lockhart-Martinelli correlation compared with data most favorably (even though only marginally so) at the lower pressure, and lowest mass velocity subsets. The other two correlations compared marginally well with data having low quality. It is obvious that these correlations are not applicable to the data covered in this study.

The Martinelli-Nelson correlation, which has been generally accepted, shows unfavorable overall results. However, for the data sets with mass velocities less than $1x10^6 lbm/hr\text{-}ft^2$ it compares very favorably. This should be expected since the data on which this correlation is based is within this mass velocity range. The Thom correlation, which is similar to Martinelli-Nelson correlation in format, is based on data with higher mass velocities. Since the Thom correlation is based on and compares well with data near the center of the mass velocity spectrum, its deviation from data having higher and lower mass velocities is less than in the case of the Martinelli-Nelson correlation, which is centered on low mass velocity data.

Different correlations will compare more favorably with different data sets, this all depends on the data, how it was reduced, the geometry and environment of the test. Any correlation can appear to be good if checked by selected data sets. However, as noted in the results of this study several compare more favorably than the others do with the entire data collection.

The four which compare most favorably with all the data are the Thom correlation, the Baroczy correlation and the homogeneous model two-phase friction multipliers given in equations (3.11) and (3.12). These are recommended for general application in the range of data covered in this work.

The breakdown of these results by property groups offers the opportunity to identify that correlation which is most appropriate over a specific property range. This is not recommended for any sets based on a small number of points (for instance fewer than 50 since a few erroneous or "bad" points could have a noticeable effect with a small data set. Some reservation is also expressed if the method of calculation differs from the method used here to reduce the data. However, this study did show that overall the use of different reduction methods had only small effects.

The mean correlation error for a particular correlation and property group and the correlation value obtained for a point within that property group substituted into equation 5.1 would yield in a friction multiplier more representative of the data studied here.

As previously mentioned the results and recommendations of this study are only valid in the range of data studied. In terms of nuclear reactor technology, this indicates that the data is applicable to boiling water reactors. For the analysis of boiling water reactors the Armand-Treschev correlation is recommended for qualities below 0.3 and the Baroczy correlation is recommended for higher qualities.

For applicability to pressurized water reactors a similar study should be conducted on steam-water pressure drop data at higher pressures than those examined here.

REFERENCES

1. J. G. Collier, Convective Boiling and Condensation, McGraw-Hill, London, 1972.

2. G. B. Wallis, One-Dimensional Two-Phase Flow, McGraw-Hill, New York, 1969.

3. L. S. Tong, Boiling Heat Transfer and Two-Phase Flow, John Wile & Sons, New York, 1965.

4. A. A. Armand, "The Resistance During the Movement of a Two-Phase System in Horizontal Pipes," AERE-Trans. 828, March 1959.

5. R. W. Lockhart and R. C. Martinelli, "Proposed Correlation of Data for Isothermal Two-Phase, Two Component Flow in Pipes," Chemical Engineering Progress, Vol. 45, No. 1, Jan. 1949.

6. R. C. Martinelli and D. B. Nelson, "Prediction of Pressure Drop During Forced-Circulation Boiling of Water," Trans. ASME, Aug. 1948.

7. D. S. Rowe, "COBRA-II: A Digital Computer Program for Thermal-Hydraulic Subchannel Analysis of Rod Bundle Nuclear Fuel Elements," BNWL-1229, Feb. 1970.

8. D. S. Rowe, "COBRA-IIIC: A Digital Computer Program for Steady State and Transient Thermal-Hydraulic Analysis of Rod Bundle Nuclear Fuel Elements," BNWL-1695, Mar. 1973.

9. A. A. Armand and G. G. Treschev, "Investigation of the Resistance During the Movement of Steam-Water Mixtures in a Heated Boiler Pipe at High Pressures," AERE-Lib/Trans. 816, Jan. 1959.

10. R. B. Bowring, "HAMBO, A Computer Program for the Subchannel Analysis of the Hydraulic and Burnout Characteristics of Rod Clusters," AEEW-R-582, Jan. 1968.

11. A. B. Jones, "Hydrodynamic Stability of a Boiling Channel," KAPL-2170, Oct. 1961.

12. S. Levy, "Steam Slip - Theoretical Prediction From Momentum Model," ASME paper 59-HT-15, 1959.

13. S. G. Bankoff, "A Variable Density Single-Fluid Model for Two-Phase Flow with Particular Reference to Steam-Water Flow," Journal of Heat Transfer, Nov. 1960.

14. Sze-Foo Chien and N. Ibele, "Pressure Drop and Liquid Film Thickness of Two-Phase Annular and Annular-Mist Flows," ASME paper 62-WA-170, 1962.

15. J. R. S. Thom, "Prediction of Pressure Drop During Forced Circulation Boiling of Water," Int. J. Heat Mass Transfer, Vol. 7, 1964.

16. C. J. Baroczy, "A Systematic Correlation for Two-Phase Pressure Drop," Chemical Engineering Progress Symposium Series, No. 64, 1968.

17. K. M. Becker et al, "An Experimental Study of Pressure Gradients for Flow of Boiling Water in Vertical Round Ducts (Part 4)," AE-86, 1962.

18. V. M. Borishansky et al, "Some Problems of Heat Transfer and Hydraulics in Two-Phase Flows," Int. J. Heat Mass Transfer, Vol. 16, 1973.

19. D. Chisholm, Pressure Gradients Due to Friction During the Flow of Evaporating Two-Phase Mixtures in Smooth Tubes and Channels," Int. J. Heat Mass Transfer, Vol. 16, 1973.

20. C. Lombardi and E. Peddrochi, "A Pressure Drop Correlation in Two-Phase Flow," Energia Nucleare, Vol. 19, No. 2, Feb. 1972.

21. N. M. Rohsenow and H. Y. Choi, Heat, Mass and Momentum Transfer, Prentice-Hall, Englewood Cliffs, N.J., 1961.

22. R. V. Macbeth, "The Effect of 'Crud' Deposits on the Functional Pressure Drop in a Boiling Channel," AEEW-R 767, Apr. 1972.

23. O. Baker, "Design of Pipelines for Simultaneous Flow of Oil and Gas," Oil and Gas Journal, July 26, 1954.

24. Sher, N. C. and Green, S. J.," Boiling Pressure Drop in Thin Rectangular Tubes," Chemical Engineering Progress Symposium Series, No. 23, 1959.

25. R. T. Lahey, Jr., "Two-Phase Flow in Boiling Water Nuclear Reactors," NEDO-13388, Jul. 1974.

26. S. J. Kline and F. A. McClintock, "Describing Uncertainties in Single Sample Experiments" Mechanical Engineering, Jan. 1953.

27. N. C. Sher, "Review of Martinelli and Nelson Pressure Drop Correlations," WAPD-TH-219, Jul. 1956.

28. "A Research Program in Two-Phase Flow," CISE, Jan. 1961.

29. G. P. Gaspari et al, "Pressure Drops in Steam-Water Mixtures," CISE-R-83, Jan. 1964.

30. E. Janssen and J. A. Kervinen, "Two-Phase Pressure Drop in Straight Pipes and Channels: Steam-Water Mixtures at 600 to 1400 psia," GEAP-4616, May 1964.

31. A. Era et al, "Heat Transfer Data in the Liquid Deficient Region for Steam-Water Mixtures at 70 kg/cm^2 Flowing in Tubular and Annular Conduits," CISE-R-184, June 1966.

32. E. Jannsen and J. A. Kervinen, "Developing Two-Phase Flow in Tubes and Annuli," Part I, GEAP-10341, Feb. 1971.

33. R. W. Haywood et al, "Experimental Study of Flow Conditions and Pressure Drop of Steam-Water Mixtures," Proc. Inst. Mechanical Engineering, Vol. 175, No. 13, 1961.

34. W. F. Davidson et al, "Studies of Heat Transmission through Boiler Tubing at Pressures From 500 to 3300 Pounds," Trans. ASME, Vol, 65, 1943.

35. R. T. Lahey, Jr., et al, "Two-Phase Flow and Heat Transfer in Multirod Geometries: Subchannel and Pressure Drop Measurements in a Nine-Rod Bundle for Diabatic and Adiabatic Conditions," GEAP-13049, Mar. 1970.

36. N. Adorni et al, "Description of a Steam Loop for Heat Transfer Experiment with Steam-Water Mixtures (Part I) and of Pressure Drop Measurements in Adiabatic Conditions (Part II)," CISE-R-62, Dec. 1962.

37. L. Berkowitz et al, "Results of Wet Steam Cooling Experiments: Pressure Drop, Heat Transfer and Burnout Measurements with Round Tubes," CISE-R-27, Oct. 1960.

38. O. Mendler et al, "Natural-Circulation Tests with Water at 800 to 2000 psia Under Non-Boiling, Local Boiling and Bulk Boiling Conditions," ASME paper 60-HT-36, June 1960.

39. B. Carnahan et al, "Applied Numerical Methods," John Wiley and Sons, New York, 1969.

40. U. K. Steam Tables in S. I. Units, Edward Arnold, London, 1970.

Appendix A

TWO-PHASE FRICTION MULTIPLIER UNCERTAINTY

A.1 General

The uncertainty in the value of the two-phase friction multiplier is calculated using the method of Kline and McClintock [26]. The uncertainty is defined as the possible value of error that the data might have. For an observation the error is the actual difference between the true and observed values. The uncertainty in experimental data is a function of the measuring instruments, the apparatus, recording method and environment associated with the particular experiment. Most pressure drop data is considered the result of single-sample experiment, since a particular case is not repeated and if so, not sufficiently to analyze the data spread by statistical methods. The experimenter must, therefore, estimate an uncertainty interval instead of computing a frequency distribution.

Consider the variable v_i whose value in an experiment is the data point m_i for which the estimated uncertainty interval is $\pm w_i$ or

$$v_i = m_i \pm w_i . \tag{A.1}$$

Now, let R be a function of n independent variables v_i,

$$R = R(v_1, v_2, v_3, \ldots, v_n) . \tag{A.2}$$

The corresponding uncertainty interval of R is then given by

$$w_R = \left[\left(\frac{\partial R}{\partial v_1} w_1\right)^2 + \left(\frac{\partial R}{\partial v_2} w_2\right)^2 + \left(\frac{\partial R}{\partial v_3} w_3\right)^2 + \cdots + \left(\frac{\partial R}{\partial v_n} w_n\right)^2\right]^{\frac{1}{2}} . \tag{A.3}$$

One unresolved matter concerning this result is the significance of this possible error range. No matter how minute the probability of an error exceeding a specified interval, the possibility always exists. The significance of the interval is the understood likelihood that it will not be exceeded. If the uncertainties w_i equations (A.1) and (A.3) are not exceeded by more than one value in ten, for instance, then this is the significance of the interval w_R. A significance on the order of one of ten or twenty is suitable for engineering applications. Another connotation for the same ranges of significance is a confidence level of 90 or 95 percent in the interval. If a particular error is presumed to have a Gaussian or normal distribution it may be expressed as a standard deviation σ_i in which case equation (A.3) can be rewritten

$$\sigma_R = \left[\left(\frac{\partial R}{\partial v_1} \sigma_1\right)^2 + \left(\frac{\partial R}{\partial v_2} \sigma_2\right)^2 + \left(\frac{\partial R}{\partial v_3} \sigma_3\right)^2 + \cdots + \left(\frac{\partial R}{\partial v_n} \sigma_n\right)^2\right]^{\frac{1}{2}} . \tag{A.4}$$

The standard deviation is used by some experimenters [28, 24, 36, 37] to define the interval and significance of the uncertainty in their recordings. Others have specified a confidence level [30]. Many researchers have not denoted the significance of their interval. It can only be assumed that they are of engineering significance. There is data published that does not even address the subject of uncertainty of error in measurements.

The pressure drop in a given two-phase flow situation is compared to a correlation by computing the friction multiplier based on the data and the correlation. The value calculated from the correlation is assumed to have no error. Equation (A.3) is applied to the appropriate relations, which reduce the experimental data to a friction multiplier, to determine the uncertainty in that multiplier.

A.2 The Uncertainty in Recorded Data

Table 5.2 gives values of error intervals reported for various pressure drop experiments. The 1961 CISE report "A Research Program in Two-Phase Flow" [28] used the standard deviation as the measure of data uncertainty because of its recognized statistical significance. However, it indicated that the values of the standard deviation were maximum errors determined from nameplate data, tests and estimates. (Maximum error is assumed to indicate an error of engineering significance) for each of the variables reported. Later reports [29, 36] from the same laboratory use the standard deviation also, but make no claim that the values used were maxima or not. A review of the assumed deviations indicates a strong likelihood that the values represented a range of accuracy that was of engineering significance. Thus, all the uncertainty ranges specified in table 5.2 are considered to be of a suitable level of confidence.

In evaluating correlations the range of uncertainty of data must be known. Should the deviation from the data of more than one correlation be within the accuracy of that data the resulting evaluation must consider them to be of equal suitability over the range of the data. For those data sets for which the accuracy has been published, the uncertainty in the multiplier are evaluated using the given error ranges. All other data points (those without given uncertainty information) are evaluated using a median uncertainty. These values are also given in Table 5.2.

A.3 Uncertainty in the Adiabatic Two-Phase Friction Multiplier

For the adiabatic pressure drop the expression for the two phase friction multiplier is

$$\phi_{fo}^{2} = \frac{\Delta P - \Delta P_{z}}{\dfrac{2 f_{fo} G^{2} L}{g_{c} \rho_{f} D}} \tag{A.5}$$

where $\Delta P_{z} = \frac{gL}{g_{c}} \left[\rho_{g} \bar{\alpha} + \rho_{f} (1-\bar{\alpha}) \right]$

and the acceleration pressure drop is presumed to be negligible in adiabatic flow. The pressure drop and dimensions are the only directly measured variables. The other variables are calculated from measurements of mass flow, pressure addition and heat losses. The uncertainties in the calculated variables of equation (A.5) are generated by applying equation (A.3) to the formulae used to compute those variables. One term of the expression can be written as

$$\frac{\partial \phi_{fo}^2}{\partial \Delta P}\,\delta\Delta P = \left[\lim_{\delta\Delta P\to o} \frac{\phi_{fo}^2(\Delta P+\delta\Delta P) - \phi_{fo}^2(\Delta P)}{\delta\Delta P}\right]\delta\Delta P. \qquad (A.6)$$

Assuming that $\delta\Delta P$ is sufficiently close to zero for numerical evaluation, equation (A.6) can be rewritten

$$\frac{\partial \phi_{fo}^2}{\partial \Delta P}\,\delta\Delta P = \phi_{fo}^2(\Delta P+\delta\Delta P) - \phi_{fo}^2(\Delta P). \qquad (A.7)$$

Then for the computer solution,

$$\delta\phi_{fo}^2 = \left[\phi_{fo}^2(\Delta P+\delta\Delta P) - \phi_{fo}^2(\Delta P)\right]^2 + \left[\phi_{fo}^2(P+\delta P) - \phi_{fo}^2(P)\right]^2 + \left[\phi_{fo}^2(x+\delta x) - \phi_{fo}^2(x)\right]^2 + \left[\phi_{fo}^2(G+\delta G) - \phi_{fo}^2(G)\right]^2 {}^{\frac{1}{2}}. \qquad (A.8)$$

The pressure P and quality x are in this expression because the properties and void fractions are functions of them. It is assumed there is no geometry uncertainty. Similar methodology is used to compute the uncertainty for diabatic pressure drop data.

Figure A.1 gives the uncertainty in the multiplier computed from a set of adiabatic data [18] as a function of quality. Figure A.2 displays the major components of uncertainty which for this case were due to uncertainty in measurement of pressure drop and mass velocity. The presentations of the two figures are related to each other by equation (A.8). The behavior of these two components of the multiplier uncertainty is predictable. Consider first the uncertainty in the pressure drop measurement only. Equation (A.4) can be written

$$\delta\phi^2_{fo}{}_{\Delta P} = \left|\frac{\partial\phi^2_{fo}}{\partial\Delta P}\delta\Delta P\right| . \tag{A.9}$$

Substituting equation (A.5) into equation (A.9) and dividing both sides by equation (a.9) gives

$$\frac{\delta\phi^2_{fo}}{\phi^2_{fo}}\Bigg._{\Delta P} = \left|\frac{\delta\Delta P}{\Delta P-\Delta P_z}\right| \tag{A.10}$$

as the uncertainty due to pressure drop alone. It can be seen from equation (A.5) that as the quality approaches zero followed by the void fraction, the gravity pressure drop increases to the value it would have if it were for a single phase liquid. At high qualities the gravity pressure drop decreases by a factor on the order of twenty. Equation (A.8) then reduces to

$$\frac{\delta\phi^2_{fo}}{\phi^2_{fo}}\Bigg._{\Delta P} \approx \left|\frac{\delta\Delta P}{\Delta P}\right| . \tag{A.11}$$

If the gravity pressure drop is considered negligible. Figure A.2 verifies these predicted limits. Similarly, for the case of the affect of uncertainty due to mass velocity alone

$$\frac{\delta\phi^2_{fo}}{\phi^2_{fo}}\Bigg._{G} \approx \left|\frac{1.75\delta G}{G}\right| . \tag{A.12}$$

This result is approximate because of the approximation of the liquid only friction factor is

$$f = \frac{.079}{\left(\frac{GD}{\mu_f}\right)^{.25}}. \qquad (A.13)$$

Equation (A.9) agrees with the results, based on data, which are given in Figure A.2. In that the uncertainty contribution of the mass velocity is independent of quality.

In most experiments the variable recorded is not the mass velocity but the mass flow rate. Consequently, the errors cannot be applied strictly in the terms of equation (A.5).

The range of uncertainty is known for independent variables such as, power to the boiler, and, inlet feed water temperature and yet the recorded value of thse variables are not given. The uncertainty effects of the latter two variables are, thus, more difficult to apply. For instance, the quality required to determine the void fraction is based on an energy balance,

$$x = \frac{1}{h_{fg}} \left[h_{in} + \frac{\Phi_1}{W} - h_{losses} - h_f \right]. \qquad (A.14)$$

In most cases the losses can be presumed to be small. Applying equation (A.3) yields

$$\delta_x = \frac{1}{h_{fg}} \left[\left(\frac{\partial x}{\partial h_{in}} \partial h_{in} \right)^2 + \left(\frac{\partial x}{\partial \Phi_1} \delta \Phi_1 \right)^2 + \left(\frac{\partial x}{\partial W} \delta W \right)^2 \right]^{\frac{1}{2}}. \qquad (A.15)$$

Now since

$$\frac{\partial x}{\partial \Phi_1} = \frac{1}{W}, \quad \frac{\partial x}{\partial W} = -\frac{\Phi_1}{W^2} \qquad (A.16)$$

and assuming that

$$h_{in} \simeq C_p \; T_{in}, \tag{A.17}$$

the uncertainty in quality can be expressed as

$$\delta_x = \frac{1}{h_{fg}} \left\{ \left(\frac{\Phi_1}{W}\right)^2 \left[\left(\frac{\delta\Phi_1}{\Phi_1}\right)^2 + \left(\frac{\delta_W}{W}\right)^2 \right] + (C_p \delta T_{in})^2 \right\}^{\frac{1}{2}}. \tag{A.18}$$

In many adiabatic experiments the inlet temperature to the boiler heating the liquid to test conditions is low and if so

$$\frac{\Phi_1}{W} \simeq h. \tag{A.19}$$

Then

$$\delta = \frac{1}{h_{fg}} \left\{ h^2 \left[\left(\frac{\delta\Phi_1}{\Phi_1}\right)^2 + \left(\frac{\delta W}{W}\right)^2 \right] + \delta T_{in}^{\;2} \right\}^{\frac{1}{2}}. \tag{A.20}$$

The components of the uncertainty in the quality due to each of the variables are

$$\delta x_{\Phi} = \frac{h}{h_{fg}} \frac{\delta\Phi_1}{\Phi_1}, \tag{A.21}$$

$$\delta_{x_W} = \frac{h}{h_{fg}} \frac{\delta_W}{W} \tag{A.22}$$

And

$$\delta x_{T_{in}} = \frac{\delta T_{in}}{h_{fg}}. \tag{A.23}$$

When the error in mass flow rate is applied in equation (A.8), its effect on both the mass velocity and quality is simultaneously evaluated in the term computing the error due to mass flow rate. There will be a term evaluating the error due to uncertainty in the boiler inlet temperature and another for the uncertainty in the boiler heat flux. Thus, the multiplier uncertainty, equation (A.8), can be expressed as

$$
\begin{aligned}
\delta\phi^2_{fo} = & \left[\phi^2_{fo}(\Delta P+\delta\Delta P) - \phi^2_{fo}(\Delta P)\right]^2 + \left[\phi^2_{fo}(P+\delta P) - \phi^2_{fo}(P)\right]^2 \\
& + \left[\phi^2_{fo}(x+\delta x_W, G+\delta G_W) - \phi^2_{fo}(s,G)\right]^2 \\
& + \left[\phi^2_{fo}(x+\delta x_\phi) - \phi^2_{fo}(x)\right]^2 \\
& + \left[\phi^2_{fo}(x+\delta x_{T_{in}}) - \phi^2_{fo}(x)\right]^{2\ \frac{1}{2}} . \qquad \text{(A.24)}
\end{aligned}
$$

A.4 Uncertainty in a Diabatic Two-Phase Friction Multiplier

The uncertainty in the diabatic result can be computed in exactly the same manner as the uncertainty in the adiabatic multiplier. The behavior of the error range is much different though. The error range in diabatic data is strongly influenced by the inlet subcooling or quality and the change as the flow travels through the test section.

The inlet condition of the flow dictates the upper limit of the elevation pressure drop of the flow. The uncertainty in the multiplier will approach the limiting value of the adiabatic condition as the heat transferred to the flow decreases to zero. As the heat flux is increased the elevation term decreases in conjunction with the mean density. This change in quality also gives rise to an acceleration pressure drop. The acceleration has the same effect on the multiplier uncertainty due to ΔP as does the gravity pressure drop, namely

$$\left(\frac{\delta\bar{\phi}^2_{fo}}{\bar{\phi}^2_{fo}}\right)_{\Delta P} = \left|\frac{\delta\Delta P}{\Delta P-\Delta P_z-\Delta P_a}\right| . \qquad (A.25)$$

As the acceleration term increases the multiplier uncertainty does also. The other effect that the acceleration term reflects strongly is the error range of the mass velocity.

The uncertainty of the multiplier due to the mass velocity for a diabatic case can be expressed as

$$\left(\frac{\delta\bar{\phi}^2_{fo}}{\bar{\phi}^2_{fo}}\right)_{G} = \left|\frac{\frac{\partial\bar{\phi}^2_{fo}}{\partial G}\,\delta G}{\bar{\phi}^2_{fo}}\right| . \qquad (A.26)$$

The expression for the average two-phase friction multiplier is

$$\bar{\phi}^2_{fo} = \frac{\Delta P-\Delta P_z-\Delta P_a}{\frac{2f_{fo}G^2L}{g_c\rho_f D}} \qquad (A.27)$$

Assuming the friction factor given by equation (A.13) applies, equation (A.27) can be written as

$$\bar{\phi}^2_{fo} = \frac{\Delta P-\Delta P_z-G^2K_a}{G^{1.75}\;K_b} \qquad (A.28)$$

for convenience. Then

$$\frac{\partial\bar{\phi}^2_{fo}}{\partial G} = -\frac{1.75(\Delta P-\Delta P_z)}{G^{2.75}\;K_b} - \frac{.25\;K_a}{G^{.75}\;K_b} . \qquad (A.29)$$

Substituting equations (A.28) and (A.29) into equation (A.27) gives

$$\left(\frac{\delta\bar{\phi}^2_{fo}}{\bar{\phi}^2_{fo}}\right)_G = \left|\frac{-1.75(\Delta P-\Delta P_z) - .25\ \Delta P_a}{\Delta P-\Delta P_z-\Delta P_a}\right| \frac{\delta G}{G}. \qquad (A.30)$$

The friction pressure drop can be written as

$$\Delta P_f = \Delta P-\Delta P_z-\Delta P_a. \qquad (A.31)$$

This equation substituted into equation (A.30) gives

$$\left(\frac{\delta\bar{\phi}^2_{fo}}{\bar{\phi}^2_{fo}}\right)_G = \left| - \frac{1.75\ \Delta P_f + 2\Delta P_a}{\Delta P_f}\right| \frac{\delta G}{G}, \qquad (A.32)$$

which also shows an increasing multiplier uncertainty caused by an increasing acceleration term. Figure A.3 is a plot of multiplier uncertainty which slows the increase in incertrainty due to larger quality changes, hence, acceleration pressure drops. Figure A.4 breaks down a segment of the data of the previous figure into uncertainties in the multiplier due to the error ranges in mass velocity and pressure drop.

Inlet subcooling complicates the error analysis immensely. If the subcooling is large or the outlet quality very small the error range in the multiplier due to uncertainty in the pressure drop measurement may be very large. The uncertainty in the multiplier due to ΔP uncertainty is

$$\left(\frac{\partial\bar{\phi}^2_{fo}}{\bar{\phi}^2_{fo}}\right)_{\Delta P} = \frac{\delta\Delta P}{\Delta P-\Delta P_z-\Delta P_a-\Delta P_{fsc}}. \qquad (A.33)$$

If the error in measuring pressure drop could amount to 2.5 percent and the subcooled length amounts to 90 percent of the tube, the two-phase friction pressure drop would amount to perhaps five percent of the total. For such a case the error in the multiplier is 50 percent. There could certainly be even more extreme cases.

The uncertainty of all errors will have greater effects for subcooled inlet conditions. Intuitively, this could be expected. Since the two-phase friction pressure drop is small relative to the overall all pressure drop. Small changes in these other components of the pressure drop would be relatively large with respect to the two-phase friction drop.

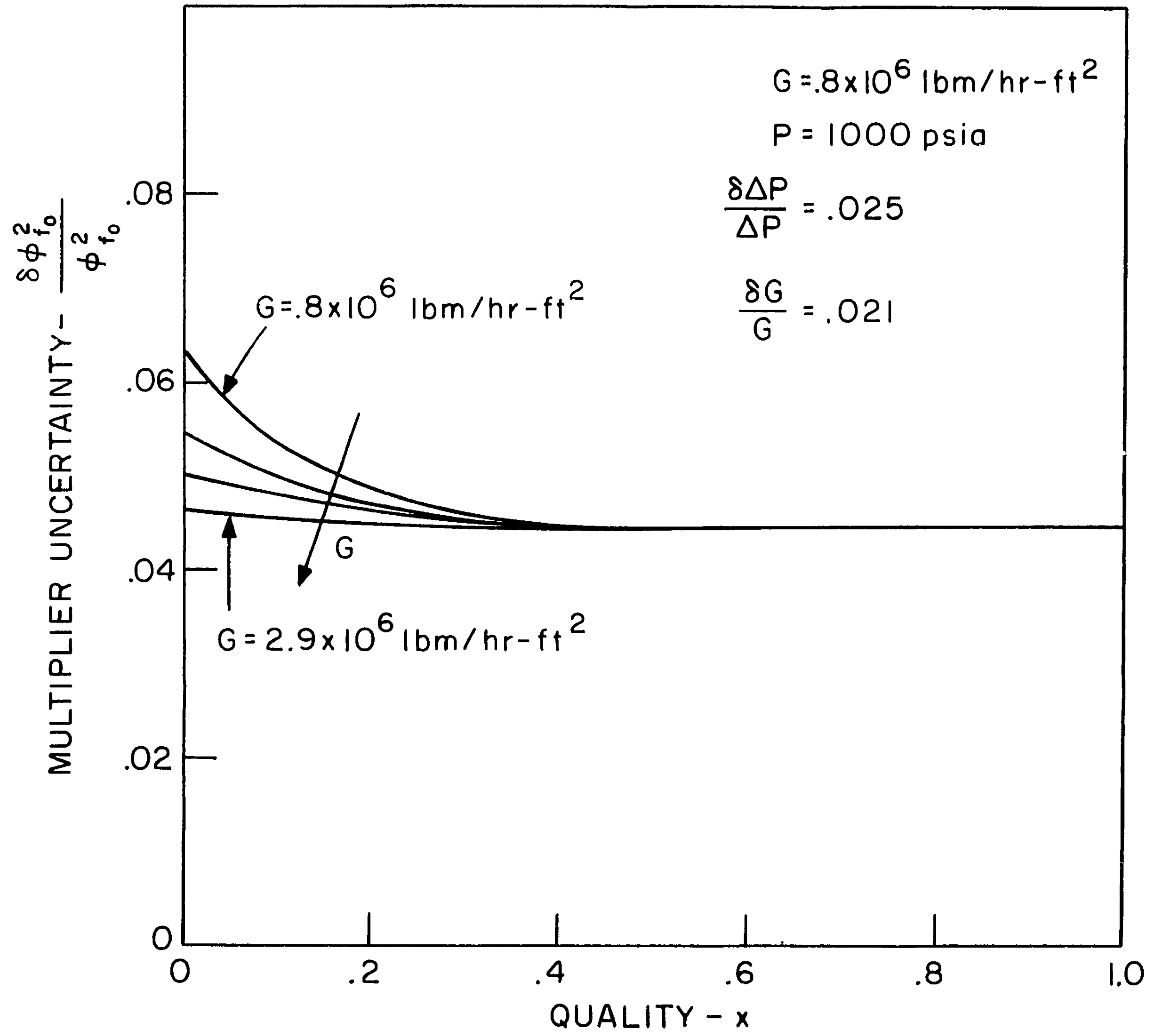


FIGURE A.1 MULTIPLIER UNCERTAINTY FOR ADIABATIC DATA.

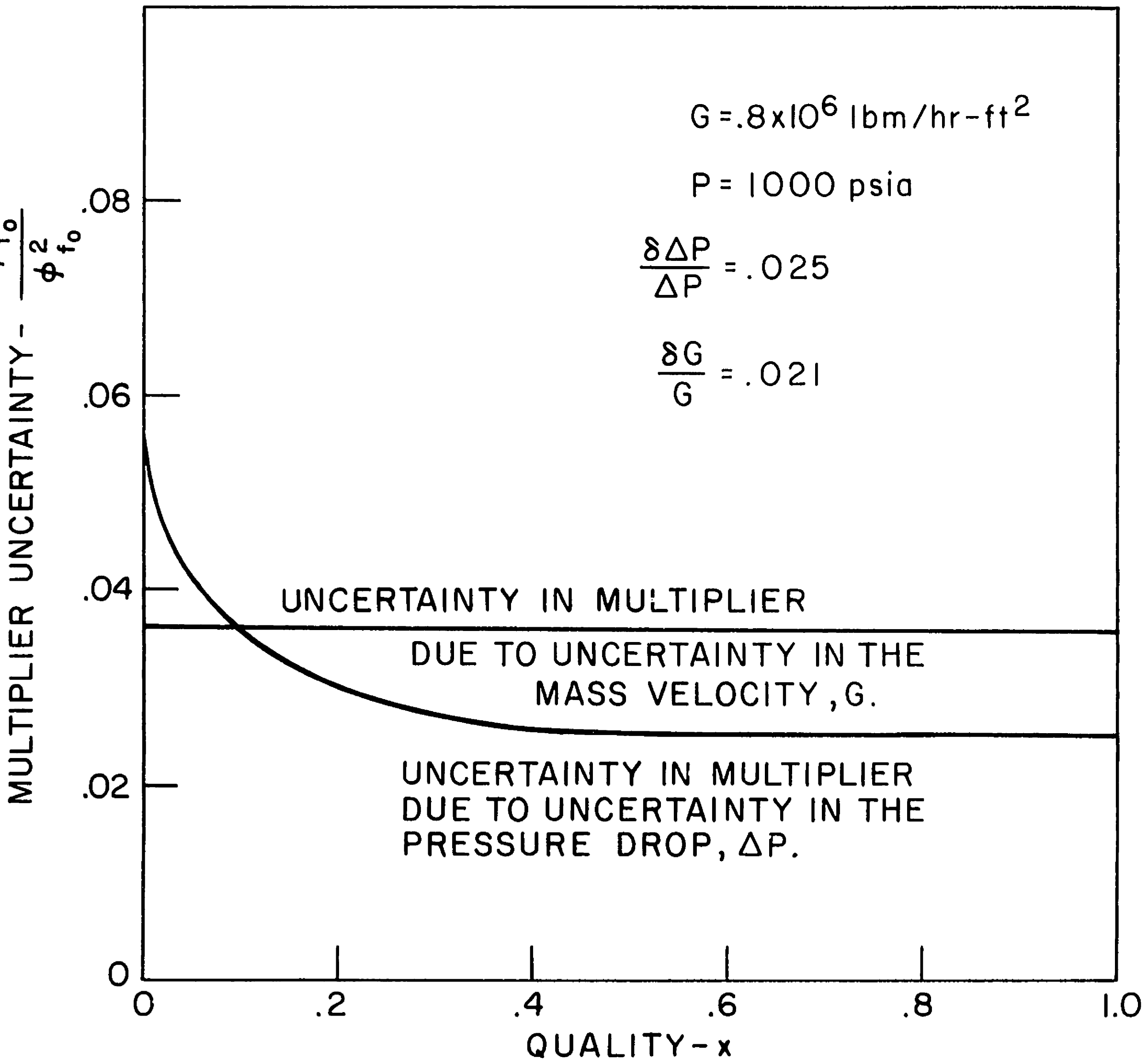


FIGURE A.2 MAJOR COMPONENTS OF MULTIPLIER UNCERTAINTY FOR A TYPICAL ADIABATIC CONDITION.

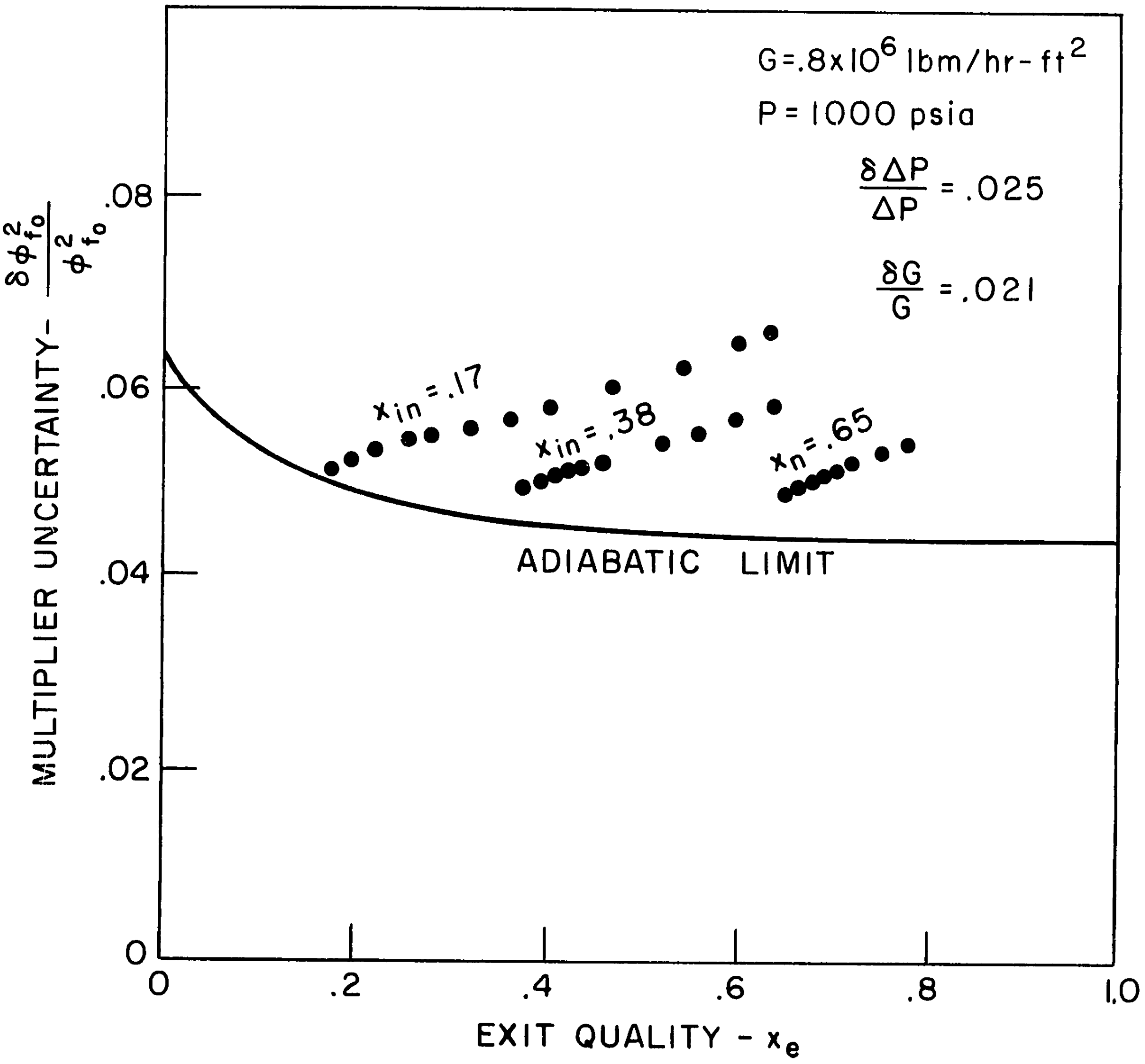


FIGURE A.3 TYPICAL MULTIPLIER UNCERTAINTY FOR DIABATIC DATA.

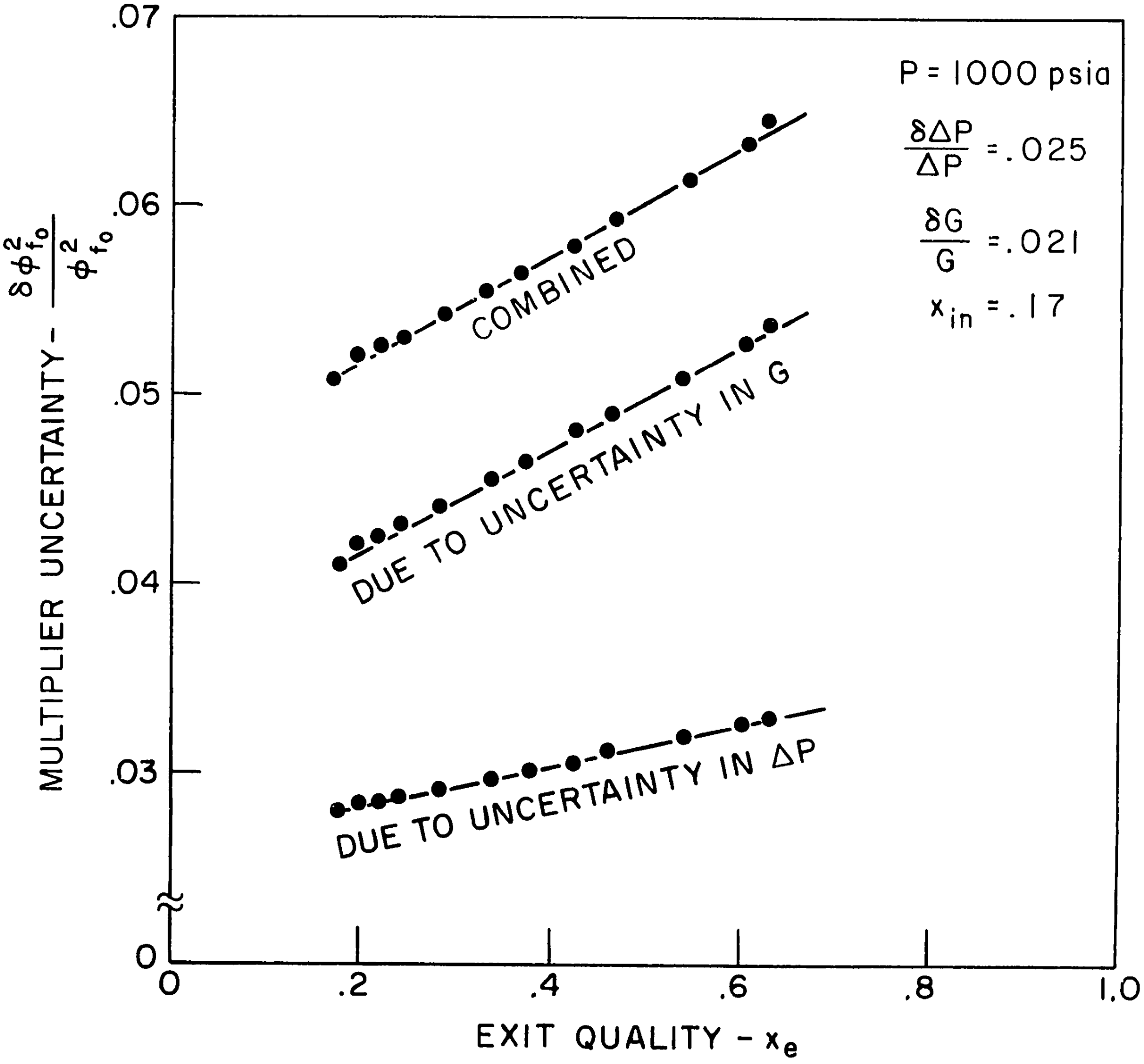


FIGURE A.4 COMPONENTS OF MULTIPLIER UNCERTAINTY FOR A TYPICAL DIABATIC CASE.

Appendix B

DATA REDUCING PROGRAMS

B.1 The Programs

Pressure drop data presented in the literature is found in different formats and expressed in different systems of units. To facilitate evaluation of correlations and models, the data was reduced to a common form for adiabatic and diabatic data. A basic program to reduce data was written for each of these two types of flows. Program statements were altered to apply the appropriate unit conversions, convert gradients to pressure drops, mass flow rate to mass velocity, and enter the data uncertainty as required by each particular data set. In adiabatic data the quality may be expressed as a mean or else the inlet and outlet values are given. For subcooled diabatic data the subcooling may be indicated by the temperature, the specific enthalpy, or by a negative quality. These were accounted for by adjusting the program for each data source. The output data of the data reduction programs is the input to the correlation evaluation program. The English system of units is used for the output. The output for adiabatic data identifies the data set and point, gives the geometry and flow conditions and expresses the pressure drop as a two-phase friction multiplier, as defined by equation (2.18). The uncertainty in the multiplier is also given. For diabatic data the output is similar, except that inlet and outlet qualities, the heat flux and an average multiplier is given.

The main program reads the number of data sets, the uncertainty intervals of the independent variables, the number of points in the set and geometry. It then reads the data points expressed as a pressure, mass velocity, quality and pressure drop. Unit conversion is handled by the main program. It calls subroutine PHI to calculate the two phase multiplier and the terms required to calcualte the uncertainty interval by equation (A.6). Finally it punches the output and proceeds to the next data point.

Subroutine PHI calculates the two-phase friction multipliers. It calculates densities and liquid viscosities by the method used in the reactor code HAMBO [10]. The acceleration and static head pressure drops are calculated and subtracted from the total pressure drop. Subroutine FRICT gives the friction factor which in the case of the sample program is the smooth tube, liquid only, friction factor. This value is used in subroutine PHI to calcualte the two-phase multiplier assuming the entire flow is liquid.

For diabatic data the program is essentially the same as for diabatic data. The average static head loss is calculated by integration as opposed to use of the mean of the inlet and outlet qualities and the resulting multiplier is the quality average multiplier.

In the following section a sample data reduction program is given. This program shows a typical input and gives the output.

B.2 A Sample Program

A sample data reduction program is listed in this section. This program is used to reduce the data of reference 29. The sample data set consists of 27 points. Both the input and output are listed.

For this example the homogeneous void fraction model and the smooth tube friction factor are used to reduce the data.

```
C THIS PROGRAM CONVERTS PRESSURE DROP DATA AS GIVEN IN CISE-R-83
C TO TWO-PHASE FRICTION MULTIPLIERS.
C THE OUTPUT IS PUNCHED CARDS FOR INPUT TO THE CORRELATION
C EVALUATION PROGRAM.
C READ IN NUMBER OF DATA SETS
      READ(5,101) ISETS
C READ IN UNCERTAINTIES FOR INDEPENDENT VARIABLES
      READ(5,103)DM,DD,DP,DDP,DQ,DT
      DO 7 K=1 ,ISETS
C READ IN NUMBER OF POINTS AND GEOMETRY
      READ(5,102)ICONF,N,DHYD,AREA,XL
C UNIT CONVERSION
      AREA=AREA/6.452
      XL=XL/(2.54*12.)
      DHYD=DHYD/2.54
      DO 7 L=1,N
C READ IN DATA POINTS
      READ(5,103) G,QUALI,QUALE,P,DELP
      QUAL=(QUALE+QUALI)/2.
      G=G*7373.
      P=P*14.22
      DELP=DELP*14.22
C CALCULATE MULTIPLIER
      CALL PHI(G,QUALI,QUALE,P,DELP,DHYD,XL,PHIACT)
C CALCULATE UNCERTAINTY IN MULTIPLIER
      D1=DHYD + DD * DHYD
      G1=G+G*DM
      G2=G/(1.+DD)**2
      HF=360.+.163*P
      HFG=880.-.222*P
      X1=DQ*(QUAL+HF/HFG)
      X2=DM*(QUAL+HF/HFG)
      X3=DT/HFG
      DP1=DELP+DELP*DDP
      P1=P+DP
      XI1=QUALI+X1
```

```
      XE1=QUALE+X1
      IF(XI1.GE.1.) XI1=QUALI-X1
      IF(XE1.GE.1.) XE1=QUALE-X1
      XI3=QUALI+X3
      XE3=QUALE+X3
      IF(XI3.GE.1.) XI3=QUALI-X3
      IF(XE3.GE.1.) XE3=QUALE-X3
      XI2=QUALI+X2
      XE2=QUALE+X2
      IF(XI2.GE.1.) XI2=QUALI-X2
      IF(XE2.GE.1.) XE2=QUALE-X2
      CALL PHI(G,QUALI,QUALE,P,DP1,DHYD,XL,PHI1)
      CALL PHI(G,QUALI,QUALE,P1,DELP,DHYD,XL,PHI2)
      CALL PHI(G,XI1,XE1,P,DELP,DHYD,XL,PHI3)
      CALL PHI(G1,XI2,XE2    ,P,DELP,DHYD,XL,PHI4)
      CALL PHI(G2,QUALI,QUALE,P,DELP,D1  ,XL,PHI5)
      CALL PHI(G ,XI3,XE3,    P,DELP,DHYD,XL,PHI6)
      DPHI=((PHI1-PHIACT)**2+(PHI2-PHIACT)**2+(PHI3-PHIACT)**2
     1+(PHI4-PHIACT)**2+(PHI5-PHIACT)**2+(PHI6-PHIACT)**2)**.5
C PUNCH OUTPUT
 7    WRITE(7,109)K,L,ICONF,DHYD,AREA,G,P,QUAL,PHIACT,DPHI
 109  FORMAT(           3I5,2F8.5,F10.1,F8.1,3F10.5)
 101  FORMAT(I3)
 102  FORMAT(I2,I3,3F5.0)
 103  FORMAT(6F10.0)
      END
```

```
      SUBROUTINE PHI (G,QUALI,QUALE,P,DELP,DHYD,XL,PHIACT)
C CALCULATES TWO PHASE FRICTION MULTIPLIER
      QUAL=(QUALE+QUALI)/2.
      U=ALOG(P)
      IF(P.LE.450.) GO TO 13
      U=U-7.
      V=(((((-.2638E-03*U+.1427E-02)*U+.2125E-02)*U+.1192E-02)*U
     1+.1974E-02)*U+.4047E-02)*U+.2196E-01
      PV=(((((.4746E01*U-.6591E01)*U-.2243E02)*U-.2797E02)*U
     1-.5301E02)*U-.6151E02)*U+.44E03
      GO TO 12
 13   V=(((((((.468E-08*U-.747E-07)*U+.3969E-06)*U-.3695E-06)*U
     1-.2049E-05)*U+.6746E-05)*U+.3313E-04)*U+.1039E-03)*U+.1614E-01
      PV=(((((((-.186E-05*U-.1201E-03)*U+.6722E-03)*U-.3071E-02)*U
     1-.6311E-02)*U+.6E-01)*U+.1104E01)*U+.1926E02)*U+.3336E03
 12   RHOF=1./V
      RHOG=P/PV
 24   U=ALOG(P)
      IF (P.LE.265.) GO TO 14
      U=U-7.
      H=((((((-.5873*U+.1149E01)*U+.7415E01)*U+.108E02)*U+.1389E02)*U
     1+.3749E02)*U+.1608E03)*U+ 557.2
      GO TO 20
 14   H=(((((((((-.4771E-04*U+.8462E-03)*U-.5339E-02)*U+.1204E-01)*U
     1+.1389E02)*U-.6628E-01)*U+.4103E-01)*U+.2877)*U+.2223E01)*U
     2+.3332E02)*U+69.8
 20   XMUF=.008+118./H
      IF(H.GE.90.) GO TO 11
      XMUF=.008+118./(H+.25*(90.-H))
 11   REFO=G*DHYD/(12.*XMUF)
      PE=P-DELP
      AI=1./(1.+(RHOG/RHOF)*((1.-QUALI)/QUALI))
      AE=1./(1.+(RHOG/RHOF)*((1.-QUALE)/QUALE))
      DPA=(((QUALE**2./AE)-(QUALI**2./AI))/RHOG+((1.-QUALE)**2./(1.-AE)
     1-(1.-QUALI)**2./(1.-AI))/RHOF)*G**2./(.4169E09*XL)
      A=(AE+AI)/2.
```

```
DPZ=RHOG*A+RHOF*(1.-A)
CALL FRICT(RHOF,DHYD,XMUF,F,G)
PHIACT=(144.*DELP/XL-DPA-DPZ )*(RHOF*DHYD )/(.5756E-07*F    *G**2)
RETURN
END
```

```
      SUBROUTINE FRICT(RHOF,DHYD,XMUF,F,G)
C CALCULATES SMOOTH TUBE FRICTION FACTOR
      REFO=G*DHYD/(12.*XMUF)
      I=1
      F=.005
 1    RF=SQRT(F)
      FF=4.*RF*ALOG10(REFO*RF)-.4*RF
      IF(ABS(F-F/FF).LE..00005) GO TO 2
      F=F/FF
      I=I+1
      IF(I.EQ.20) F=0.
      GO TO 1
 2    RETURN
      END
```

```
INPUT DATA TO DATA REDUCTICN PROGPAM
FIRST CARD:  NUMBER OF DATA SETS
SECOND CARD:  DATA RECORDING UNCERTAINTIES
THIRD CARD:  GEOMETRY AND NUMBER OF POINTS
DATA POINTS IN ORIGINAL UNITS

  1
.006        .01         5.          .025        .02         2.
 1 27.807  .514 67.5
301.97      .83138      .83104      71.142      1.1045
300.81      .78064      .78055      71.203      .98279
301.27      .69243      .69267      71.267      .85347
300.81      .6177       .61817      71.304      .78065
300.58      .53546      .53617      71.328      .73168
301.97      .43268      .43354      71.388      .61115
301.04      .35622      .35713      71.434      .52075
301.97      .27449      .2754       71.48       .42784
301.97      .2217       .22264      71.423      .40174
301.51      .15901      .15993      71.449      .34874
300.35      .08889      .08968      71.49       .26838
301.97      .02226      .02286       71.321     .18426
390.53      .56874      .5697       71.659      1.0543
390.53      .49426      .4955       71.623      .98656
391.01      .42073      .42206      71.431      .87858
390.53      .3527       .35405      71.386      .75679
392.43      .27872      .28005      71.341      .63501
390.53      .23227      .23362      71.403      .58227
390.53      .20104      .2024       71.415      .55716
391.48      .15368      .15502      71.442      .50443
392.43      .10919      .11041      71.552      .42533
391.01      .05492      .05587      71.4        .30605
220.57      .89497      .89452      71.28       .68774
218.93      .79862      .79849      71.361      .59608
221.97      .66778      .66798      71.34       .56721
221.73      .57769      .57807      71.265      .50568
221.5       .5112       .5117       71.282      .47304
```

```
OUTPUT CARDS PUNCHED, COLUMNS FOR:
DATA SET NUMBER, POINT NUMBER, CONFIGURATION, EQUIVALENT DIAMETER, AREA,
MASS VELOCITY, PRESSURE, AVG QUALITY, MULTIPLIER(DATA),
MULTIPLIER UNCERTAINTY

    1    1     1 0.31772 0.07967 2226424.0   1011.6    0.83121  13.96092    0.78368
    1    2     1 0.31772 0.07967 2217872.0   1012.5    0.78059  12.49524    0.70174
    1    3     1 0.31772 0.07967 2221263.0   1013.4    0.69255  10.79996    0.60708
    1    4     1 0.31772 0.07967 2217872.0   1013.9    0.61793   9.88888    0.55633
    1    5     1 0.31772 0.07967 2216176.0   1014.3    0.53581   9.26287    0.52163
    1    6     1 0.31772 0.07967 2226424.0   1015.1    0.43311   7.64215    0.43094
    1    7     1 0.31772 0.07967 2219568.0   1015.8    0.35667   6.51972    0.36809
    1    8     1 0.31772 0.07967 2226424.0   1016.4    0.27494   5.28651    0.29901
    1    9     1 0.31772 0.07967 2226424.0   1015.6    0.22217   4.93639    0.27956
    1   10     1 0.31772 0.07967 2223033.0   1016.0    0.15947   4.24217    0.24094
    1   11     1 0.31772 0.07967 2214481.0   1016.6    0.08929   3.17073    0.18247
    1   12     1 0.31772 0.07967 2226424.0   1014.2    0.02256   1.87346    0.13686
    1   13     1 0.31772 0.07967 2879377.0   1019.0    0.56922   8.29183    0.46767
    1   14     1 0.31772 0.07967 2879377.0   1018.5    0.49488   7.74204    0.43728
    1   15     1 0.31772 0.07967 2882916.0   1015.7    0.42140   6.86430    0.38813
    1   16     1 0.31772 0.07967 2879377.0   1015.1    0.35337   5.90666    0.33441
    1   17     1 0.31772 0.07967 2893385.0   1014.5    0.27938   4.88695    0.27719
    1   18     1 0.31772 0.07967 2879377.0   1015.4    0.23294   4.50124    0.25561
    1   19     1 0.31772 0.07967 2879377.0   1015.5    0.20172   4.29283    0.24398
    1   20     1 0.31772 0.07967 2886381.0   1015.9    0.15435   3.83934    0.21862
    1   21     1 0.31772 0.07967 2893385.0   1017.5    0.10980   3.17650    0.18156
    1   22     1 0.31772 0.07967 2882916.0   1015.3    0.05539   2.19944    0.12876
    1   23     1 0.31772 0.07967 1626262.0   1013.6    0.89474  15.16887    0.85233
    1   24     1 0.31772 0.07967 1614170.0   1014.8    0.79855  13.30265    0.74800
    1   25     1 0.31772 0.07967 1636584.0   1014.5    0.66788  12.31999    0.69330
    1   26     1 0.31772 0.07967 1634815.0   1013.4    0.57788  10.98125    0.61840
    1   27     1 0.31772 0.07967 1633119.0   1013.6    0.51145  10.27097    0.57876
```

Appendix C

THE CORRELATION EVALUATION PROGRAMS

C.1 The Program for Adiabatic Data

This program computes the multipliers for the eighteen models and correlations and then compares them with the data. The difference value, ε, is computed for each correlation. Cumulative mean values, R.M.S. values, and standard deviations of ε are successively calculated for each point. The results for each data set and the entire data collection are printed at the end of each data set.

The main program reads in tabular correlation and property matrices and the data points, calculates correlations and the evaluation measures and prints the output. Those correlations which have been presented in Chapter 4 in a closed form are calculated directly. For the Lockhart-Martinelli correlation ϕ^2_{fo} is computed using the approximation given as equation (4.25). The Martinelli-Nelson correlation is interpolated using the log of the pressure, as was done by Bowring in HAMBO [10], and a third order Lagrangian polynomial. Similar interpolation was used to find the multiplier for the Thom, and Baroczy correlations. The Borishansky correlation was directly interpolated using third order Lagrangian polynomial. The

Levy momentum exchange model void fraction computation is accomplished by an iterative method. The main program also compares each of the correlation results with the data and computes the mean, RMS and standard deviation values for the difference value.

Subroutine PROP calculates the densities and viscosities. The saturated vapor viscosity is interpolated by a third order Lagrangian polynomial from the 1963 International Skeleton Table [40]. The remainder are calcualted as in the reactor code HAMBO. Subroutine TERP sets up two-dimensional correlation matrices for interpolation using the log of one axis, such as pressure for the Thom and Martinelli-Nelson correlations and the property index for the Baroczy correlation. Function FLAGR is given in Carnahan et al [39] and was used to interpolate using Lagrangian polynomials. Subroutine FRICT iterates as solution to the smooth tube friction factor.

Should this program be used to compare diabatic pressure drop data, it would have to be altered to calculate a mean multiplier for each correlation. The multiplier would be averaged over the quality range from inlet to outlet conditions.

A sample program is given in the following chapter.

C.2 A Sample Program

A sample adiabatic correlation evaluation program is listed in this section. This example evaluates the output of the previous chapter's sample program. All of the tabular correlation and property data is listed. The data points are not listed since they are given in the previous section.

```
C CORRELATION EVALUATION PROGRAM FOR ADIABATIC DATA.
C DATA FROM DATA CONVERSION PROGRAM
C INPUT VARIABLES
C       M    DATASET NUMBER
C       L    POINT NUMBER
C     ICONF  CONFIGURATION
C            2  ANNULUS
C            OTHERS AS DESIRED
C     DHYD   EQUIVALENT DIAMETER   IN
C     AREA   AREA IN**2
C       G    MASS VELOCITY LBM/HR-FT**2
C       P    PRESSURE PSIA
C      QUAL  QUALITY
C    PHIACT  LIQUID ONLY TWO-PHASE FRICTION MULTIPLIER
C     DPHI   UNCERTAINTY RANGE FOR MULTIPLIER
C INPUT FORMAT   SEE STATEMENT 102
C LAST DATA CARD MUST BE FOLLOWED BT BLANK CARD
C CARDS FOR EACH DATA SET MUST BE LUMPED TOGETHER
      COMMON                                    XMUGT(29),PMUGT(29)
      DIMENSION PHI(20)
      DIMENSION PT(6),PHIT(6,13),XT(13)
      DIMENSION GDEV(20),GSUSQ(20),GSUM(20),GXERR(20),GRERR(20)
      DIMENSION XMN(13),QMN(13),PMN(9),PHIMN(9,13),
     1SUSQ(20),SUM(20),XNERR(20),RERR(20),DEV(20),
     2GB(5),ERR(20),PHIB(11,15),BPI(11),BPIC(8),XB(15),XBC(10),
     3CORR(8,10,5),XBO(11),FBO(11),PSIG(20),SIG(20)
C INITIALIZE VARIABLES
      NC=18
      MM=1
      N=0
      NN=0
      SPHI=0.
      GSPHI=0.
      SPHI2=0.
      GSPHI2=0.
      DO 12 I=1,20
```

```
      GSUM(I)=0.
      GSUSQ(I)=0.
      SUM(I)=0.
 12   SUSQ(I)=0.
C READ IN VAPOR VISCOSITY AND SURFACE TENSION MATRICES
      READ(5,103)(XMUGT(I),I=1,29),(PMUGT(I),I=1,29)
      READ(5,103)(PSIG(I),I=1,20),(SIG(I),I=1,20)
 103  FORMAT(16F5.0)
C READ IN VARIOUS CORRELATION MULTIPLIER MATRICES
      READ(5,104)(XMN(I),I=1,13)
 104  FORMAT(13F5.0)
      READ(5,105)(PT(I),I=1,6),((PHIT(I,J),I=1,6),J=1,13)
 105  FORMAT(6F5.0/(6F5.0))
      READ(5,106)(PMN (I),I=1,9),((PHIMN(I,J),I=1,9),J=1,13)
 106  FORMAT(9F5.0/(9 F5.0))
      READ(5,114)(BPI(I),I=1,11),(XB(J),J=1,15),((PHIB(I,J),I=1,11),
     1J=1,15)
 114  FORMAT(11F5.1/15F5.1/(11F5.1))
      READ(5,115)(BPIC(I),I=1,8),(XBC(J),J=1,10),(GB(K),K=1,5),
     1(((CORR(I,J,K),I=1,8),J=1,10),K=1,5)
 115  FORMAT(8F5.1/10F5.1/5F10.1/(8F5.1))
      READ(5,107)(XBO(I),I=1,11),(FBO(I),I=1,11)
 107  FORMAT(11F5.0)
      GO TO 3
 2    N=N+1
      NN=NN+1
C READ IN DATA
 3    READ (5,102)M,L,ICONF,DHYD,AREA,G,P,QUAL,PHIACT,DPHI
 102  FORMAT(3I5,2F8.5,F10.1,F8.1,3F10.5)
C CHECK IF END OF DATA SET THEN EVALUATE RATING PARAMETERS AND PRINT
      IF(MM.EQ.M) GO TO 4
      DO 17 I=1,NC
      DEV(I)=SQRT(SUSQ(I)/FLOAT(N)-(SUM(I)/FLOAT(N))**2 )
      XNERR(I)=SUM(I)/FLOAT(N)
      GDEV(I)=SQRT(GSUSQ(I)/FLOAT(NN)-(GSUM(I)/FLOAT(NN))**2)
```

```
      GRERR(I)=SQRT(GSUSQ(I)/FLOAT(NN))
 17   RERR(I)=SQRT(SUSQ(I)/FLOAT(N))
      GXPER=GSPHI/FLOAT(NN)
      GRXPER=SQRT(GSPHI2/FLOAT(NN))
      RXPER=SQRT(SPHI2/FLOAT(N ))
      XPER=SPHI/FLOAT(N)
      WRITE(6,108)
 108  FORMAT('1'///////10X,'   DATA SET  POINTS  DATA MN  DATA RMS  CORR
     1ELATION  CORRELATION  CORRELATION  CORRELATION'/32X,'ERROR    ERRO
     2R',18X,'MN  ERROR    RMS ERROR    STD   DEV'/)
      WRITE(6,101)MM,N,XPER,RXPER,(I,XNERR(I),RERR(I),DEV(I),I=1,NC)
      WRITE(6,1010)
 1010 FORMAT('1'///////10X,'  DATA SETS  POINTS  DATA MN  DATA RMS  CORR
     1ELATION  CORRELATION  CORRELATION  CORRELATION'/32X,'ERROR    ER
     2R',18X,'MN  ERROR    RMS ERROR    STD   DEV'/)
      WRITE(6,101)MM,NN,GXPER,GRXPER,(I,GXERR(I),GRERR(I),GDEV(I),I=1,NC
     1)
 101  FORMAT(10X,2I9,2F9.5/(50X,I9,3F13.5))
      SPHI=0.
      SPHI2=0.
      N=0
      DO 11 I=1,20
      SUM(I)=0.
 11   SUSQ(I)=0.
      MM=M
      IF(MM.EQ.0) STOP
 4    CONTINUE
      CALL PROP (P ,RHOG,RHOF,XMUF,XMUG)
      REG=(DHYD*G*QUAL)/(12.*XMUG)
      REF=(DHYD*G*(1.-QUAL))/(12.*XMUF)
C HOMOGENEOUS MODELS
      PHI(1)=1.+QUAL*(RHOF/RHOG-1.)
      PHI(2)=PHI(1)/(1.+QUAL*(XMUF/XMUG-1.))**.25
      PHI(3)=PHI(1)*(1.+QUAL*(XMUG/XMUF-1.))**.25
      PHI(4)=PHI(1)*((1.+QUAL*(XMUG*RHOF/(RHOG*XMUF)-1.))/PHI(1))**.25
```

```
      BETA=1./((RHOG/RHOF)*(1.-QUAL)/QUAL+1.)
      IF (BETA-.9)51,51,52
 51   ALPHA=.833*BETA
      GO TO 53
 52   C1=.69+(1.-BETA)*(4.+ .000724*G*AREA*(1.-QUAL))
      C2=4.*C1*REF**.125*(RHOG/RHOF)**.5
      ALPHA=1.-(4.+1.144*C2)/(5.+C2*(BETA/(1.-BETA)+1.144))
 53   IF(ALPHA.GE..9) GO TO 57
      IF(ALPHA-.65)54,54,55
 54   PHI(5)=(1.-QUAL)**1.75/(1.-ALPHA)**1.42
      GO TO 56
 55   PHI(5)=.478*(1.-QUAL)**1.75/(1.-ALPHA)**2.2
      GO TO 56
 57   PHI(5)=1.73*(1.-QUAL)**1.75/(1.-ALPHA)**1.64
C ARMAND-TRESCHEV CORRELATION
 56   ALPHA=(.833+.05*ALOG10(P/14.22))*BETA
      IF(ALPHA-.5)58,58,59
 58   PHI(6)=((1.-QUAL)**1.75)/(1.-ALPHA)**1.2
      GO TO 60
 59   PHI(6)=(.48*(1.-QUAL)**1.75)/(1.-ALPHA)**(1.9+.000104*P)
      IF(BETA.GT..9)PHI(6)=(.000176*P+.005)*((1.-QUAL)/(1.-BETA))**1.75
C LOCKHART-MARTINELLI CORRELATION
 60   IF(REF-2000.)61,61,62
 61   IF(REG-2000.)63,63,64
 63   Q=1.
      R=1.
      CF=16.
      CG=16.
      C1=5.
      GO TO 65
 64   Q=1.
      R=.2
      CF=16.
      CG=.046
      C1=12.
      GO TO 65
```

```
 62   IF (REG-2000.)66,66,67
 66   Q=.2
      R=1.
      CF=.046
      CG=16.
      C1=10.
      GO TO 65
 67   Q=.2
      R=.2
      CF=.046
      CG=.046
      C1=20.
 65   XLM=SQRT(((REG**R)/(REF**Q))*(CF/CG)*(RHOG/RHOF)*((1./QUAL)-1.)
     1**2.)
      PHI(7)=(1.+C1/XLM+1./XLM**2.)*(1.-QUAL)**1.75
C MARTINELLI-NELSON CORRELATION
      DO 1 I=1,13
 1    QMN(I)=XMN(I)
      NI=9
      NJ=13
      CALL TERP(PMN,P,QMN,QUAL,PHIMN,PHI(8),NI,NJ)
C BANKOFF MODEL
      C1=.71+.0001*P
      ALPHA=C1/(1.+(RHOG/RHOF)*(1./QUAL-1.))
      PHI(9)=(1.-ALPHA*(1.-RHOG/RHOF))**.75*(1.-QUAL*(1.-RHOF/RHOG))
     1**1.75*(1.-QUAL)**1.75
C MARTINELLI-NELSON-JONES CORRELATION
      IF(G-700000.)86,86,87
 86   PHI(10)=PHI(8)*(1.36+.0005*P+.1E-06*G-.714E-09*G*P)
      GO TO 88
 87   PHI(10)=PHI(8)*(1.26-.0004*P+119000./G+280.*P/G)
C LEVY MOMENTUM EXCHANGE MODEL
 88   AA=QUAL
      XQUAL1=0.
      AA1=0.
      NCNT=0
```

```
 83   XQUAL=(AA*(1.-2.*AA)+AA*SQRT((1.-2.*AA)**2 +AA*(2.*(RHOF/RHOG)*
     1(1.-AA)**2+AA*(1.-2.*AA))))/(2.*(RHOF/RHOG)*(1.-AA)**2+AA*(1.-
     22.*AA))
      NCNT=NCNT+1
      IF (NCNT-21)85,85,84
 84   AA=0.
      GO TO 80
 85   IF(ABS(QUAL-XQUAL)-.001)80,80,82
 82   SLOPE=(AA-AA1)/(XQUAL-XQUAL1)
      AA1=AA
      XQUAL1=XQUAL
      AA=AA+SLOPE*(QUAL-XQUAL)
      IF(AA-1.)83,83,81
 81   AA=1.
      GO TO 83
 80   PHI(11)=(1.-QUAL)**1.75/(1.-AA)**2
C SZE-FOO CHIEN AND IBELE CORRELATION
      IF(REG*(REF)**.301-1199000.)90,90,91
 90   PHIG=3.885E-06*REG**.71*REF**.725
      GO TO 92
 91   PHIG=3.425*REF**.517/REG**.34
 92   PHI(12)=PHIG*(XMUG/XMUF)**.25*(RHOF/RHOG)*QUAL**1.75
C THOM CORRELATION
      DO 5 I=1,13
 5    XT(I)=XMN(I)
      NI=6
      NJ=13
      CALL TERP (PT,P,XT ,QUAL,PHIT,PHI(13),NI,NJ)
C BAROCZY CORRELATION
      BPII=(RHOF/RHOG)/(XMUF/XMUG)**.2
      NI=11
      NJ=15
      CALL TERP (BPI,BPII,XB,QUAL,PHIB,PHI(14),NI,NJ)
      K=1
      IF(G-250000.)170,171,171
 171  IF(G-3000000.)72,172,172
```

```
 170  K=2
      GO TO 70
 172  K=5
      GO TO 70
 72   IF (G-GB(K)) 70,71,71
 71   K=K+1
      GO TO 72
 70   K1=1
 75   IF(BPII-BPIC(K1)) 73,74,74
 74   K1=K1+1
      GO TO 75
 73   K2=1
 78   IF(QUAL-XBC(K2))76,77,77
 77   K2=K2+1
      GO TO 78
 76   XMULT=(ALOG(BPII)-ALOG(BPIC(K1-1)))/(ALOG(BPIC(K1))
     1-ALOG(BPIC(K1-1)))
      YMULT=(QUAL-XBC(K2-1))/(XBC(K2)-XBC(K2-1))
      ZMULT=(G-GB(K-1))/(GB(K)-GB(K-1))
      CORRX1=XMULT*(CORR(K1,K2,K )-CORR(K1-1,K2   ,K))+CORR(K1-1,K2,K)
      CORRX2=XMULT*(CORR(K1,K2-1,K)-CORR(K1-1,K2-1,K))+CORR(K1-1,K2-1,K)
      CORRX3=XMULT*(CORR(K1,K2,K-1)-CORR(K1-1,K2,K-1))+CORR(K1-1,K2,K-1)
      CORRX4=XMULT*(CORR(K1,K2-1,K-1)-CORR(K1-1,K2-1,K-1))+
     1CORR(K1-1,K2-1,K-1)
      CORRY1=YMULT*(CORRX1-CORRX2)+CORRX2
      CORRY2=YMULT*(CORRX3-CORRX4)+CORRX4
      CORRZ=ZMULT*(CORRY1-CORRY2)+CORRY2
      PHI(14)=PHI(14)*CORRZ
C BECKER CORRELATION
      PHI(15)=1.+32000.*(QUAL/P)**.96
C BORISHANSKY CORRELATION
      IDEG=3
      NB=11
      MIN=3
 175  IF(QUAL-XBO(MIN))173,174,174
 174  MIN=MIN+1
```

```
      GO TO 175
  173 IF(MIN.GE.10) MIN=10
      MIN=MIN-2
      FB=FLAGR(XBO,FBO,QUAL,IDEG,MIN,NB)
      PHI(16)=FB*((XMUG/XMUF)**.25*(RHOF/RHOG)-1.)+1.
C CHISHOLM CORRELATION
      GAMMA =(RHOF/RHOG)**.5*(XMUG/XMUF)**.125
      IF(GAMMA-9.5)180,180,181
  180 IF(G-369000.)182,182,183
  182 B=4.8
      GO TO 184
  183 B=1.77E06/G
      IF(G.GE.1.4E06) B=1494./G**.5
      GO TO 184
  181 IF(G-442600.)185,185,186
  185 B=14123./(G**.5*GAMMA)
      GO TO 184
  186 B=21./GAMMA
  184 IF(GAMMA.GE.28.) B=  407500./(GAMMA**2*G**.5)
      PHI(17)=1.+(GAMMA**2-1.)*(B*(QUAL*(1.-QUAL))**.875+QUAL**1.75)
C C.I.S.E. CORRELATICN
      I=3
      IDEG=3
      NS=20
      PA=P/14.503
  152 IF(PA-PSIG(I))150,151,151
  151 I=I+1
      GO TO 152
  150 IF(I.GE.19)I=19
      I=I-2
      SIGMA=FLAGR(PSIG,SIG,PA,IDEG,I,NS)
      XK=.087
      XN=1.4
      IF(ICONF.NE.2) GO TO 153
      XN=1.6
      XK=.0354
```

```
 153  DPCORR=(XK/27140.)*(G/7373.)**XN*((62.42/RHOF)*(1.+QUAL*
     1(RHOF/RHOG-1.)))**.86*SIGMA**.4/(2.54*DHYD)**1.2
      CALL FRICT(RHOF,DHYD,XMUF,F,G)
      DPCALC=(2.*F*(G/3600.)**2)/(RHOF*DHYD*144.*32.17)
      PHI(18)=DPCORR/DPCALC
C COMPARE WITH DATA MULTIPLIER
      PDPHI=DPHI/PHIACT
      SPHI=SPHI+PDPHI
      SPHI2=SPHI2+PDPHI**2
      GSPHI=GSPHI+PDPHI
      GSPHI2=GSPHI2+PDPHI**2
      DO 16 K=1,NC
      ERR(K)    =( PHI(K)-PHIACT)/PHIACT
      GSUM(K)=GSUM(K)+ERR(K)
      GSUSQ(K)=GSUSQ(K)+ERR(K)*ERR(K)
      SUM(K)=SUM(K)+ERR(K)
 16   SUSQ(K)=SUSQ(K)+ERR(K)*ERR(K)
      GO TO 2
      END
```

```
      SUBROUTINE PROP (P,RHOG,RHOF,XMUF,XMUG)
C CALCULATES DENSITIES AND VISCOSITIES
      COMMON                                    XMUGT(29),PMUGT(29)
      U=ALOG(P)
      IF(P.LE.450.) GO TO 9
      U=U-7.
      V=(((((-.2638E-03*U+.1427E-02)*U+.2125E-02)*U+.1192E-02)*U
     1+.1974E-02)*U+.4047E-02)*U+.2196E-01
      PV=(((((.4746E 01*U-.6591E01)*U-.2243E02)*U-.2797E02)*U
     1-.5301E02)*U-.6151E01)*U+.44E03
      GO TO 12
 9    V=(((((((.468E-08*U-.747F-07)*U+.3969E-06)*U-.3695E-06)*U
     1-.2049E-05)*U+.6746E-05)*U+.3313E-04)*U+.1039E-03)*U+.1614E-01
      PV=(((((((-.186E-05*U-.1201E-03)*U+.6722E-03)*U-.3071E-02)*U
     1-.6311E-02)*U+.6E-01)*U+.1104E01)*U+.1926E02)*U+.3336E03
 12   RHOF=1./V
      RHOG=P/PV
      U=ALOG(P)
      IF (P.LE.265.) GO TO 7
      U=U-7.
      H=((((((-.5873*U+.1149E01)*U+.7415E01)*U+.108E02)*U+.1389E02)*U
     1+.3749E02)*U+.1608E03)*U+ 557.2
      GO TO 20
 7    H=(((((((((-.4771E-04*U+.8462E-03)*U-.5339E-02)*U+.1204E-01)*U
     1+.1389E02)*U-.6628E-01)*U+.4103E-01)*U+.2877)*U+.2223E01)*U
     2+.3332E02)*U+69.8
 20   XMUF=.008+118./H
      IF(H.GE.90.) GO TO 11
      XMUF=.008+118./(H+.25*(90.-H))
 11   PA=P/14.503
      IDEG=3
      J=29
      I=3
 3    IF(PA-PMUGT(I))2,1,1
 1    I=I+1
      GO TO 3
```

```
2     IF(I.GE.28)I=28
      I=I-2
6     XMUG=FLAGR(PMUGT,XMUGT,PA,IDEG,I,J)
      XMUG=XMUG*2418.9/1000000.
      RETURN
      END
```

```
      SUBROUTINE TERP (XX,X,YY,Y,PHI,PHI3,NI,NJ)
C SETS UP MULTIPLIER MATRICES FOR INTERPOLATION
      DIMENSION XX(NI),YY(NJ),PHI(NI,NJ),XA(20),XB(4),YB(4),PHIE(4),
     1PHIA(4),PHIB(4),PHIC(4),PHID(4)
      I=1
 4    IF(X-XX(I)) 1,3,3
 3    I=I+1
      GO TO 4
 1    J=1
 6    IF(Y-YY(J)) 2,5,5
 5    J=J+1
      GO TO 6
 2    IF(NJ.EQ.15) GO TO 20
      GO TO 22
 20   IF(Y.LE..4) GO TO 22
      DO 23 K=1,NI
 23   XA(K)=XX(K)
      X1=X
      GO TO 24
 22   DO 8 K=1,NI
 8    XA(K)=ALOG(XX(K))
      X1=ALOG(X)
 24   IDEG=3
      MIN=1
      IF(I-3)10,10,11
 10   II=1
      GO TO 12
 11   IF(NI-2-I)16,16,17
 16   II=NI-4
      GO TO 12
 17   II=I-2
 12   IF(J-3)13,13,14
 13   JJ=1
      GO TO 15
 14   IF(NJ-2-J)18,18,19
 18   JJ=NJ-4
```

```
      GO TO 15
19    JJ=J-2
15    DO 7 IA=1,4
      XB(IA)=XA(II+IA-1)
      YB(IA)=YY(JJ+IA-1)
      PHIA(IA)=PHI(II+IA-1,JJ)
      PHIB(IA)=PHI(II+IA-1,JJ+1)
      PHIC(IA)=PHI(II+IA-1,JJ+2)
7     PHID(IA)=PHI(II+IA-1,JJ+3)
      PHIE(1)=FLAGR(XB,PHIA,X1,IDEG,MIN,IA)
      PHIE(2)=FLAGR(XB,PHIB,X1,IDEG,MIN,IA)
      PHIE(3)=FLAGR(XB,PHIC,X1,IDEG,MIN,IA)
      PHIE(4)=FLAGR(XB,PHID,X1,IDEG,MIN,IA)
      PHI3   =FLAGR(YB,PHIE,Y ,IDEG,MIN,IA)
      RETURN
      END
```

```
   FUNCTION FLAGR(X,Y,XARG,IDEG,MIN, N)
   DIMENSION X(N),Y(N)
    FACTOR=1.
   MAX=MIN+IDEG
    DO 2 J=MIN,MAX
   IF(XARG.NE.X(J)) GO TO 2
   FLAGR=Y(J)
   RETURN
 2 FACTOR=FACTOR*(XARG-X(J))
    YEST=0.
   DO 5 I=MIN, MAX
    TERM=Y(I)*FACTOR/(XARG-X(I))
   DO 4 J=MIN,MAX
 4 IF (I.NE.J) TERM=TERM/(X(I)-X(J))
 5 YEST=YEST+TERM
    FLAGR=YEST
   RETURN
   END
```

```
      SUBROUTINE FRICT(RHOF,DHYD,XMUF,F,G)
C CALCULATES SMOOTH TUBE FRICTION FACTOR
      REFO=G*DHYD/(12.*XMUF)
      I=1
      F=.005
 1    RF=SQRT(F)
      FF=4.*RF*ALOG10(REFO*RF)-.4*RF
      IF(ABS(F-F/FF).LE..00005) GO TO 2
      F=F/FF
      I=I+1
      IF(I.EQ.20) F=0.
      GO TO 1
 2    RETURN
      END
```

```
C PROPERTY AND CORRELATION INPUT DATA
12.0612.4512.8313.2 13.5713.9414.3 14.6615.0215.3715.7216.0716.4216.7817.1417.51
17.9 18.3118.7419.2119.7320.3 20.9521.7 22.7 24.1526.4530.6 41.4 1.0131.4331.905
2.7013.6144.76 6.18 7.92 10.0312.5515.5519.0823.2 27.9833.4839.7746.9455.0564.19
74.4585.9298.69112.9128.6146.1165.4186.7210.5221.2
1.0136.18 12.5519.0872.9833.4839.7846.9455.0564.1974.4585.9298.69112.9128.6146.1
165.4186.7210.5221.258.7846.5940.0535.5330.9 28.5626.1923.8221.4419.0716.7114.39
12.119.89 7.75 5.71 3.79 2.03 .47  0.
0.   .01  .05  .1   .2   .3   .4   .5   .6   .7   .8   .9   1.
250. 600. 1250.2100.3000.3206.
1.   1.   1.   1.   1.   1.
2.12 1.46 1.1  1.   1.   1.
6.29 2.86 1.62 1.21 1.02 1.
11.1 4.78 2.39 1.48 1.08 1.0
20.6 8.42 3.77 2.02 1.24 1.
30.2 12.1 5.17 2.57 1.40 1.
39.8 15.8 6.59 3.12 1.57 1.
49.4 19.5 8.03 3.69 1.73 1.
59.1 23.2 9.49 4.27 1.88 1.
68.8 26.9 10.194.86 2.03 1.
78.7 30.7 12.4 5.45 2.18 1.
88.6 34.5 13.8 6.05 2.33 1.
98.8638.3 15.336.6642.48 1.
14.7 100. 500. 1000.1500.2000.2500.3000.3206.
1.   1.   1.   1.   1.   1.   1.   1.   1.
5.6  3.5  1.8  1.6  1.35 1.2  1.1  1.05 1.
30.  15.  5.3  3.6  2.4  1.75 1.43 1.17 1.
69.  28.  8.9  5.4  3.4  2.45 1.75 1.3  1.
150. 56.  16.2 8.6  5.1  3.25 2.19 1.51 1.
245. 83.  23.  11.6 6.8  4.04 2.62 1.68 1.
350. 115. 29.2 14.4 8.4  4.82 3.02 1.83 1.
450. 145. 34.9 17.  9.9  5.59 3.38 1.97 1.
545. 174. 40.  19.4 11.1 6.34 3.7  2.1  1.
625. 199. 44.6 21.4 12.1 7.05 3.96 2.23 1.
685. 216. 48.6 22.9 12.8 7.7  4.15 2.35 1.
720. 210. 48.  22.3 13.  7.95 4.2  2.38 1.
```

```
525. 130. 30.  15.  8.6  5.9  3.7  2.15 1.
1.   3.33 10.  33.3 50.  66.67100. 166.7250. 500. 1000.
0.   .001 .005 .01  .035 .05  .075 .1   .15  .2   .3   .4   .6   .8   1.
1.   1.   1.   1.   1.   1.   1.   1.   1.   1.   1.
1.   1.01 1.04 1.12 1.21 1.32 1.59 1.88 2.08 2.13 2.15
1.   1.02 1.12 1.55 1.96 2.59 3.3  4.41 4.9  5.29 5.6
1.   1.06 1.22 1.81 2.4  3.46 4.8  6.86 7.8  8.12 8.8
1.   1.26 1.78 3.45 5.06 6.86 9.6  13.8 16.3 20.3 22.8
1.   1.36 2.05 4.7  6.76 8.88 12.4 18.5 22.8 28.6 34.2
1.   1.5  2.5  6.1  8.7  11.8  16.  23.  29.  37.8 48.2
1.   1.59 2.8  7.9  10.8 14.5 20.  28.  36.  50.  70.
1.   1.77 3.6  11.  15.4 20.  27.  38.  49.5 70.  108.
1.   1.93 4.2  13.2 18.5 25.4 33.5 49.  63.  96.  148.
1.   2.25 5.5  17.3 25.  31.9 43.5 62.  86.  139. 240.
1.   2.48 6.5  21.2 29.4 37.8 53.  80.  110. 190. 330.
1.   2.86 8.   26.  37.2 49.  69.  108. 155. 279. 538.
1.   3.2  9.1  30.  43.6 57.  85.  137. 203. 392. 760.
1.   3.33 10.  33.3 50.  66.67100. 166.7250. 500. 1000.
1.   7.   10.  30.  70.  100. 300. 1000.
0.   .001 .01  .05  .1   .2   .4   .6   .8   1.
250000.   500000.   1000000.  2000000.  3000000.
1.   1.   1.   1.   1.   1.   1.   1.
1.   1.11 1.17 1.22 1.19 1.17 1.17 1.4
1.   1.15 1.23 1.29 1.23 1.19 1.17 1.4
1.   1.54 1.46 1.37 1.22 1.12 1.03 1.3
1.   1.74 1.56 1.43 1.35 1.38 1.41 1.5
1.   1.74 1.56 1.43 1.35 1.38 1.41 1.5
1.   1.42 1.38 1.34 1.29 1.26 1.24 1.34
1.   1.19 1.17 1.15 1.15 1.14 1.15 1.3
1.   1.06 1.08 1.08 1.09 1.08 1.09 1.13
1.   1.   1.   1.   1.   1.   1.   1.
1.   1.   1.   1.   1.   1.   1.   1.
1.   1.08 1.08 1.09 1.1  1.1  1.12 1.2
1.   1.09 1.12 1.15 1.19 1.21 1.24 1.29
1.   1.32 1.25 1.2  1.16 1.15 1.12 1.2
1.   1.43 1.31 1.21 1.24 1.24 1.26 1.29
```

```
1.    1.55 1.39 1.25 1.24 1.23 1.22 1.26
1.    1.32 1.26 1.21 1.19 1.17 1.15 1.2
1.    1.17 1.15 1.13 1.1  1.1  1.1  1.15
1.    1.07 1.08 1.08 1.08 1.07 1.07 1.08
1.    1.   1.   1.   1.   1.   1.   1.
1.    1.   1.   1.   1.   1.   1.   1.
1.    1.   1.   1.   1.   1.   1.   1.
1.    1.   1.   1.   1.   1.   1.   1.
1.    1.   1.   1.   1.   1.   1.   1.
1.    1.   1.   1.   1.   1.   1.   1.
1.    1.   1.   1.   1.   1.   1.   1.
1.    1.   1.   1.   1.   1.   1.   1.
1.    1.   1.   1.   1.   1.   1.   1.
1.    1.   1.   1.   1.   1.   1.   1.
1.    1.   1.   1.   1.   1.   1.   1.
1.    1.   1.   1.   1.   1.   1.   1.
1.    .96  .94  .92  .89  .88  .87  .8
1.    .91  .89  .87  .77  .73  .67  .7
1.    .78  .79  .8   .74  .73  .68  .72
1.    .71  .77  .81  .77  .75  .72  .74
1.    .64  .71  .76  .74  .75  .75  .74
1.    .58  .65  .7   .74  .77  .8   .78
1.    .58  .65  .7   .77  .81  .87  .83
1.    .71  .77  .81  .86  .9   .94  .92
1.    1.   1.   1.   1.   1.   1.   1.
1.    1.   1.   1.   1.   1.   1.   1.
1.    .94  .89  .85  .81  .8   .77  .71
1.    .88  .83  .8   .54  .6   .5   .55
1.    .7   .69  .68  .6   .58  .52  .57
1.    .65  .67  .68  .64  .63  .6   .61
1.    .56  .59  .63  .62  .63  .63  .61
1.    .47  .51  .55  .6   .65  .71  .68
1.    .47  .51  .55  .64  .7   .77  .75
1.    .5   .63  .68  .76  .8   .87  .86
1.    1.   1.   1.   1.   1.   1.   1.
0.    .1   .2   .3   .4   .5   .6   .7   .8   .9   1.
```

0. .227 .443 .636 .809 .982 1.1471.2571.3751.3361.

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION   CORRELATION   CORRELATION
                   ERROR     ERROR                  MN   ERROR   RMS ERROR     STD    DEV

    1         27  0.05722   0.05730
                                                1    0.15150       0.21803       0.15679
                                                2   -0.08330       0.12319       0.09075
                                                3    0.02377       0.12465       0.12236
                                                4   -0.15985       0.17688       0.07573
                                                5    1.99231       2.80795       1.97870
                                                6    0.39069       0.50278       0.31646
                                                7    2.05045       2.17587       0.72808
                                                8    0.85032       0.88371       0.24060
                                                9   -0.21836       0.40173       0.33721
                                               10    0.90448       0.92915       0.21267
                                               11    0.89239       1.19942       0.80140
                                               12    4.84456       5.25880       2.04578
                                               13    0.13860       0.20977       0.15745
                                               14   -0.16907       0.18005       0.06192
                                               15    1.38463       1.45134       0.43495
                                               16    0.44195       0.48978       0.21110
                                               17   -0.06331       0.09644       0.07276
                                               18    0.23809       0.25294       0.08539
```

Appendix D

CORRELATION EVALUATION FOR ADIABATIC DATA SETS

The data sets in this appendix are the source sets identified in Table 5.1. The set numbers in this appendix coincide with those preceded by the letter A in that table. Table 5.1 gives the geometry and property ranges for each data set.

These results were obtained using the Thom void fraction correlation and the smooth tube single-phase friction factor to reduce the data.

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR     ERROR                  MN   ERROR   RMS ERROR    STD    DEV

     1       54  0.05885   0.06013
                                            1        0.05844      0.24280      0.23567
                                            2       -0.15637      0.22909      0.16742
                                            3       -0.04346      0.19962      0.19483
                                            4       -0.23440      0.28192      0.15663
                                            5        1.73464      2.36368      1.60561
                                            6        0.15796      0.34539      0.30715
                                            7        1.96527      2.05092      0.58652
                                            8        0.74149      0.81987      0.34981
                                            9       -0.20018      0.28527      0.20323
                                           10        0.92658      0.95387      0.22655
                                           11        0.56386      0.79317      0.55783
                                           12        4.19709      4.70770      2.13233
                                           13        0.04950      0.24068      0.23553
                                           14       -0.11751      0.17549      0.13033
                                           15        1.21099      1.31943      0.52381
                                           16        0.35837      0.45759      0.28453
                                           17       -0.01828      0.11169      0.11018
                                           18        0.27776      0.30137      0.11693
```

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION   CORRELATION   CORRELATION
                   ERROR     ERROR                  MN   ERROR    RMS ERROR     STD    DEV

    2        172  0.06260   0.06819
                                                1   -0.06021       0.25110       0.24378
                                                2   -0.24303       0.29931       0.17471
                                                3   -0.14385       0.24485       0.19814
                                                4   -0.31884       0.36068       0.16862
                                                5    1.09761       1.72020       1.32452
                                                6    0.01264       0.37675       0.37654
                                                7    1.57371       1.71883       0.69126
                                                8    0.55078       0.65330       0.35134
                                                9   -0.18222       0.31166       0.25285
                                               10    0.77830       0.82660       0.27841
                                               11    0.32827       0.72121       0.64217
                                               12    3.15809       3.70628       1.93985
                                               13   -0.05361       0.24575       0.23984
                                               14   -0.13935       0.17968       0.11343
                                               15    0.92655       1.07819       0.55136
                                               16    0.20259       0.35342       0.28959
                                               17   -0.09289       0.16859       0.14068
                                               18    0.09321       0.21332       0.19188
```

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR     ERROR                  MN   ERROR   RMS  ERROR   STD    DEV

     3        49  0.06261   0.06537
                                                1     0.05660      0.27092      0.26494
                                                2    -0.12638      0.24886      0.21438
                                                3    -0.02358      0.23612      0.23494
                                                4    -0.21110      0.29190      0.20160
                                                5     1.13033      1.95078      1.58994
                                                6     0.19244      0.39459      0.34448
                                                7     2.09423      2.22213      0.74300
                                                8     0.76610      0.86837      0.40886
                                                9    -0.10837      0.27971      0.25786
                                               10     0.90601      0.95246      0.29383
                                               11     0.42929      0.69545      0.54714
                                               12     3.74667      4.38342      2.27527
                                               13     0.04709      0.26765      0.26348
                                               14    -0.10174      0.16875      0.13463
                                               15     1.15359      1.28909      0.57530
                                               16     0.36672      0.49185      0.32777
                                               17    -0.03715      0.14433      0.13947
                                               18     0.26535      0.33412      0.20303
```

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR     ERROR                 MN   ERROR   RMS  ERROR   STD    DEV

     4       58  0.05873   0.05998
                                               1     0.04387      0.22641      0.22212
                                               2    -0.16836      0.23482      0.16370
                                               3    -0.06140      0.19594      0.18607
                                               4    -0.24322      0.28679      0.15197
                                               5     1.35896      2.00654      1.47629
                                               6     0.20489      0.37416      0.31308
                                               7     1.88268      1.99021      0.64535
                                               8     0.70590      0.78201      0.33652
                                               9    -0.23987      0.35259      0.25842
                                              10     0.89949      0.92723      0.22514
                                              11     0.59006      0.84365      0.60297
                                              12     3.96740      4.40692      1.91851
                                              13     0.03017      0.22109      0.21902
                                              14    -0.10612      0.16867      0.13110
                                              15     1.17783      1.27688      0.49309
                                              16     0.33178      0.42692      0.26867
                                              17    -0.02955      0.12640      0.12290
                                              18     0.28480      0.31267      0.12902
```

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
5	74	0.06066	0.06337				
				1	-0.05366	0.19020	0.18248
				2	-0.23604	0.27748	0.14588
				3	-0.13820	0.21684	0.16710
				4	-0.31016	0.33558	0.12813
				5	1.24064	1.99223	1.55879
				6	0.08574	0.25540	0.24058
				7	1.73130	1.85234	0.65859
				8	0.57026	0.64692	0.30545
				9	-0.25048	0.35375	0.24979
				10	0.73072	0.75806	0.20177
				11	0.36093	0.55814	0.42573
				12	3.70224	4.05666	1.65830
				13	-0.06287	0.19227	0.18170
				14	-0.19232	0.23493	0.13492
				15	0.97279	1.05333	0.40398
				16	0.22437	0.32981	0.24173
				17	-0.12059	0.15873	0.10321
				18	0.14555	0.18502	0.11423

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR     ERROR                  MN  ERROR    RMS ERROR    STD    DEV

     6        57  0.05886   0.05894
                                                1     0.08956      0.20006      0.17890
                                                2    -0.13178      0.19525      0.14407
                                                3    -0.01609      0.16118      0.16037
                                                4    -0.21368      0.24898      0.12779
                                                5     2.06548      2.77722      1.85654
                                                6     0.24854      0.35926      0.25942
                                                7     2.07609      2.17666      0.65399
                                                8     0.79105      0.84404      0.29436
                                                9    -0.17642      0.32082      0.26796
                                               10     1.00122      1.01865      0.18762
                                               11     0.61802      0.78547      0.48478
                                               12     4.75729      5.00646      1.55973
                                               13     0.07832      0.19316      0.17657
                                               14    -0.05105      0.16817      0.16024
                                               15     1.28549      1.34163      0.38404
                                               16     0.40464      0.46363      0.22632
                                               17     0.02010      0.12178      0.12011
                                               18     0.33552      0.35154      0.10490
```

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR     ERROR                  MN  ERROR    RMS ERROR    STD    DEV

     7        27  0.06905   0.07519
                                                1    -0.09130      0.23879      0.22065
                                                2    -0.26158      0.31666      0.17846
                                                3    -0.17484      0.26464      0.19865
                                                4    -0.32845      0.36506      0.15933
                                                5     1.39657      2.18632      1.68213
                                                6     0.04235      0.31038      0.30747
                                                7     1.54052      1.71071      0.74385
                                                8     0.50313      0.62131      0.36453
                                                9    -0.30777      0.41744      0.28201
                                               10     0.75802      0.81073      0.28755
                                               11     0.33965      0.62589      0.52571
                                               12     3.35400      3.87484      1.94038
                                               13    -0.10364      0.24260      0.21935
                                               14    -0.11374      0.19894      0.16322
                                               15     0.86474      0.99575      0.49369
                                               16     0.15880      0.32826      0.28729
                                               17    -0.06539      0.14761      0.13233
                                               18     0.23168      0.27654      0.15100
```

```
DATA SET  POINTS  DATA MN  DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR    ERROR                   MN  ERROR  RMS ERROR    STD    DEV

      8       61  0.06028  0.06124
                                               1    -0.15019      0.24483      0.19335
                                               2    -0.31314      0.33765      0.12631
                                               3    -0.22916      0.27321      0.14877
                                               4    -0.37640      0.39549      0.12138
                                               5     1.16688      1.91155      1.51407
                                               6    -0.03528      0.29116      0.28902
                                               7     1.39675      1.47210      0.46492
                                               8     0.40307      0.48213      0.26454
                                               9    -0.35097      0.39672      0.18495
                                              10     0.58821      0.64681      0.25425
                                              11     0.25648      0.64360      0.59029
                                              12     2.77640      3.19410      1.57920
                                              13    -0.16127      0.25029      0.19140
                                              14    -0.22552      0.25736      0.12399
                                              15     0.75858      0.88231      0.45058
                                              16     0.08703      0.23913      0.22273
                                              17    -0.18456      0.22266      0.12455
                                              18     0.28865      0.36092      0.21667
```

```
DATA SET  POINTS  DATA MN  DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR    ERROR                  MN   ERROR   RMS ERROR    STD    DEV

     9       68  0.06686  0.07497
                                              1     -0.14079      0.21695      0.16506
                                              2     -0.29412      0.32010      0.12632
                                              3     -0.21209      0.25348      0.13883
                                              4     -0.35834      0.37867      0.12239
                                              5      1.22963      2.02060      1.60338
                                              6     -0.04063      0.22659      0.22291
                                              7      1.43275      1.50870      0.47266
                                              8      0.41903      0.48546      0.24511
                                              9     -0.31257      0.36370      0.18595
                                             10      0.63738      0.66602      0.19322
                                             11      0.21060      0.48629      0.43832
                                             12      2.83277      3.33341      1.75699
                                             13     -0.15071      0.22288      0.16421
                                             14     -0.16904      0.19108      0.08910
                                             15      0.74489      0.84373      0.39626
                                             16      0.09885      0.22275      0.19962
                                             17     -0.13100      0.16758      0.10450
                                             18      0.34458      0.39242      0.18777
```

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION   CORRELATION   CORRELATION
                   ERROR     ERROR                  MN   ERROR   RMS ERROR     STD    DEV

   10       151  0.06171   0.06574
                                            1       -0.12859       0.29837       0.26924
                                            2       -0.27231       0.34391       0.21005
                                            3       -0.19470       0.30693       0.23727
                                            4       -0.33737       0.39064       0.19693
                                            5        0.81774       1.76144       1.56012
                                            6       -0.03854       0.30475       0.30230
                                            7        1.46000       1.65885       0.78754
                                            8        0.43827       0.61110       0.42586
                                            9       -0.27880       0.37671       0.25334
                                           10        0.64294       0.75763       0.40080
                                           11        0.20069       0.60307       0.56870
                                           12        2.05219       2.98861       2.17263
                                           13       -0.13918       0.30149       0.26744
                                           14       -0.17198       0.23539       0.16072
                                           15        0.73492       0.95750       0.61375
                                           16        0.10785       0.35623       0.33951
                                           17       -0.12170       0.24158       0.20868
                                           18        0.37980       0.51387       0.34613
```

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
11	51	0.05995	0.06110				
				1	0.02315	0.19918	0.19783
				2	-0.17501	0.22516	0.14166
				3	-0.08182	0.18511	0.16605
				4	-0.24637	0.27723	0.12712
				5	1.39697	2.25094	1.76499
				6	0.21900	0.40184	0.33692
				7	1.78070	1.92808	0.73934
				8	0.66277	0.73108	0.30856
				9	-0.26712	0.41443	0.31686
				10	0.84569	0.86880	0.19903
				11	0.62253	0.97932	0.75599
				12	3.80829	4.34912	2.10044
				13	0.01107	0.19843	0.19812
				14	-0.11414	0.16158	0.11437
				15	1.10621	1.20627	0.48104
				16	0.28779	0.38424	0.25459
				17	-0.04664	0.11078	0.10048
				18	0.26873	0.28265	0.08761

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR     ERROR                  MN  ERROR    RMS ERROR    STD   DEV

   12        72  0.05984   0.06141
                                              1     -0.02583      0.44957      0.44982
                                              2     -0.16478      0.39639      0.36052
                                              3     -0.08001      0.41514      0.40736
                                              4     -0.24970      0.41537      0.33194
                                              5      0.51144      1.26397      1.15587
                                              6      0.08259      0.66267      0.65751
                                              7      2.01771      2.57218      1.59529
                                              8      0.64318      0.95608      0.70739
                                              9     -0.09041      0.32936      0.31670
                                             10      0.81555      1.03541      0.63792
                                             11      0.19802      0.73869      0.71165
                                             12      2.75667      4.27473      3.26713
                                             13     -0.03441      0.42790      0.42651
                                             14     -0.06920      0.30566      0.29773
                                             15      0.96073      1.42350      1.05041
                                             16      0.26786      0.65156      0.59395
                                             17     -0.02132      0.37219      0.37157
                                             18      0.13597      0.39608      0.37201
```

```
DATA SET  POINTS  DATA MN  DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR    ERROR                  MN   ERROR   RMS ERROR    STD    DEV

   13       360  0.06589  0.07237
                                           1       -0.10883      0.18178      0.14561
                                           2       -0.25833      0.29145      0.13494
                                           3       -0.18536      0.23371      0.14234
                                           4       -0.32807      0.34933      0.12003
                                           5        0.72305      1.57298      1.39694
                                           6        0.02432      0.26936      0.26826
                                           7        1.43423      1.60364      0.71739
                                           8        0.48103      0.55331      0.27342
                                           9       -0.25290      0.39835      0.30778
                                          10        0.76371      0.79319      0.21423
                                          11        0.35630      0.98983      0.92348
                                          12        2.40852      2.92358      1.65721
                                          13       -0.10958      0.18096      0.14401
                                          14       -0.08379      0.18233      0.16194
                                          15        0.76239      0.83513      0.34089
                                          16        0.11454      0.23583      0.20614
                                          17       -0.05442      0.17200      0.16316
                                          18        0.23486      0.29046      0.17092
```

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION   CORRELATION   CORRELATION
                   ERROR     ERROR                  MN   ERROR    RMS  ERROR    STD    DEV

    14        42  0.05664   0.05664
                                                1     -0.16735       0.20515       0.11866
                                                2     -0.39627       0.40489       0.08308
                                                3     -0.30512       0.31827       0.09052
                                                4     -0.44173       0.44851       0.07771
                                                5      2.26819       2.54266       1.14911
                                                6     -0.04635       0.31552       0.31210
                                                7      0.64117       0.76905       0.42467
                                                8      0.24680       0.29658       0.16447
                                                9     -0.46856       0.55606       0.29942
                                               10      0.66044       0.68283       0.17342
                                               11      0.73720       1.34689       1.12723
                                               12      2.89056       3.02348       0.88660
                                               13     -0.13964       0.18314       0.11850
                                               14     -0.19813       0.23895       0.13357
                                               15      0.68491       0.72493       0.23753
                                               16     -0.03607       0.12890       0.12375
                                               17     -0.15280       0.19156       0.11554
                                               18      0.10345       0.18173       0.14941
```

```
DATA SET  POINTS  DATA MN  DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                  ERROR    ERROR                  MN   ERROR   RMS ERROR    STD    DEV

   15       268  0.12243  0.44381
                                              1     -0.11063     0.40997      0.39476
                                              2     -0.28553     0.47183      0.37563
                                              3     -0.18906     0.44381      0.40153
                                              4     -0.37473     0.49950      0.33027
                                              5      1.94729     3.28549      2.64622
                                              6     -0.13238     0.42537      0.40425
                                              7      1.06715     1.51270      1.07213
                                              8      0.36820     0.73160      0.63219
                                              9      0.13917     1.05480      1.04558
                                             10      0.92767     1.28772      0.89311
                                             11      0.21295     0.65335      0.61767
                                             12      2.44255     2.80165      1.37230
                                             13     -0.10929     0.42172      0.40731
                                             14      0.06852     0.52954      0.52509
                                             15      0.70246     0.93177      0.61216
                                             16      0.10854     0.50365      0.49182
                                             17      0.29273     0.78534      0.72875
                                             18      0.39950     0.87183      0.77491
```

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR     ERROR                 MN   ERROR   RMS  ERROR   STD    DEV

   16       155  0.05952   0.06065
                                           1       -0.09144      0.20062      0.17857
                                           2       -0.28441      0.31308      0.13087
                                           3       -0.21256      0.25856      0.14722
                                           4       -0.33695      0.35815      0.12140
                                           5        0.58834      1.17224      1.01391
                                           6        0.15146      0.38440      0.35330
                                           7        1.21087      1.40679      0.71615
                                           8        0.40242      0.49321      0.28515
                                           9       -0.46202      0.56972      0.33335
                                          10        0.62519      0.66496      0.22651
                                          11        0.77157      1.33977      1.09529
                                          12        2.41739      2.99065      1.76074
                                          13       -0.10748      0.20429      0.17373
                                          14       -0.18376      0.22787      0.13475
                                          15        0.87119      0.96710      0.41991
                                          16        0.08542      0.23834      0.22251
                                          17       -0.13423      0.19670      0.14379
                                          18        0.19792      0.26011      0.16877
```

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR     ERROR                  MN   ERROR   RMS  ERROR   STD     DEV

   17        66   0.05879   0.05947
                                            1       -0.14217      0.24899      0.20442
                                            2       -0.30019      0.33775      0.15483
                                            3       -0.21850      0.28131      0.17718
                                            4       -0.36421      0.39048      0.14082
                                            5        0.58526      1.28003      1.13839
                                            6        0.00397      0.29163      0.29160
                                            7        1.43179      1.57116      0.64692
                                            8        0.42031      0.52801      0.31959
                                            9       -0.33562      0.41303      0.24073
                                           10        0.61316      0.65649      0.23457
                                           11        0.25032      0.57506      0.51772
                                           12        2.67903      3.26198      1.86099
                                           13       -0.15424      0.25449      0.20243
                                           14       -0.21193      0.23623      0.10436
                                           15        0.76137      0.89556      0.47154
                                           16        0.09650      0.27874      0.26150
                                           17       -0.15568      0.19306      0.11417
                                           18        0.11964      0.18889      0.14617
```

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR     ERROR                  MN   ERROR   RMS  ERROR   STD    DEV

    18        13  0.05814   0.05817
                                                1   -0.28389      0.30049      0.09850
                                                2   -0.41944      0.42877      0.08896
                                                3   -0.34936      0.36097      0.09081
                                                4   -0.47347      0.47986      0.07808
                                                5    0.27449      0.60439      0.53846
                                                6   -0.18919      0.26642      0.18758
                                                7    1.04282      1.12305      0.41688
                                                8    0.18788      0.25543      0.17305
                                                9   -0.45278      0.49063      0.18895
                                               10    0.51815      0.55891      0.20952
                                               11    0.05012      0.34155      0.33785
                                               12    1.83277      2.06231      0.94556
                                               13   -0.29452      0.30961      0.09549
                                               14   -0.18503      0.24182      0.15570
                                               15    0.48458      0.53017      0.21510
                                               16   -0.08094      0.14857      0.12459
                                               17   -0.14849      0.21182      0.15106
                                               18    0.12067      0.20314      0.16342
```

```
DATA SET  POINTS  DATA MN  DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR    ERROR                  MN   ERROR  RMS  ERROR   STD    DEV

   19        26  0.05642  0.05642
                                           1        0.02539      0.15665      0.15458
                                           2       -0.17842      0.20852      0.10792
                                           3       -0.08816      0.15556      0.12817
                                           4       -0.24835      0.26539      0.09357
                                           5        0.90633      1.47834      1.16792
                                           6        0.26985      0.41283      0.31243
                                           7        1.73174      1.88660      0.74854
                                           8        0.64881      0.69393      0.24613
                                           9       -0.29841      0.46021      0.35035
                                          10        0.72558      0.75220      0.19834
                                          11        0.70274      1.07342      0.81140
                                          12        3.52504      3.85625      1.56356
                                          13        0.01600      0.15640      0.15558
                                          14       -0.20393      0.22391      0.09246
                                          15        1.11874      1.18609      0.39400
                                          16        0.28526      0.34748      0.19842
                                          17       -0.13504      0.14771      0.05986
                                          18        0.13563      0.15960      0.08413
```

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
20	37	0.05316	0.05333				
				1	-0.42926	0.44912	0.13208
				2	-0.50748	0.52201	0.12228
				3	-0.45874	0.47529	0.12432
				4	-0.55749	0.57052	0.12126
				5	0.09803	0.96621	0.96122
				6	-0.38548	0.41847	0.16285
				7	0.67662	0.75948	0.34496
				8	-0.03791	0.18983	0.18600
				9	-0.44389	0.46267	0.13049
				10	0.13476	0.27501	0.23973
				11	-0.31904	0.38916	0.22285
				12	0.46005	1.23712	1.14840
				13	-0.42883	0.44963	0.13516
				14	-0.38958	0.42191	0.16198
				15	0.10945	0.28885	0.26731
				16	-0.26414	0.30513	0.15276
				17	-0.35306	0.41106	0.21053
				18	-0.14463	0.28070	0.24057

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR     ERROR                  MN   ERROR   RMS  ERROR   STD    DEV

    21        23  0.08099   0.09390
                                                1     -0.44327      0.48992      0.20866
                                                2     -0.51369      0.54471      0.18118
                                                3     -0.46891      0.50902      0.19806
                                                4     -0.56346      0.58638      0.16233
                                                5     -0.04724      0.91440      0.91318
                                                6     -0.39380      0.46867      0.25411
                                                7      0.76915      1.03517      0.69281
                                                8     -0.02997      0.36589      0.36466
                                                9     -0.46834      0.51195      0.20676
                                               10      0.12334      0.43685      0.41907
                                               11     -0.34265      0.43781      0.27252
                                               12      0.86205      1.55727      1.29690
                                               13     -0.45242      0.49686      0.20539
                                               14     -0.39937      0.46209      0.23244
                                               15      0.10031      0.44989      0.43857
                                               16     -0.27220      0.38944      0.27851
                                               17     -0.38410      0.45504      0.24399
                                               18     -0.06369      0.34760      0.34172
```

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
22	22	0.15152	0.22066				
				1	-0.36784	0.37336	0.06394
				2	-0.43885	0.44434	0.06961
				3	-0.39305	0.39819	0.06377
				4	-0.49328	0.49841	0.07128
				5	0.05699	0.90451	0.90271
				6	-0.32907	0.35021	0.11984
				7	0.95062	1.00918	0.33875
				8	0.09188	0.15776	0.12824
				9	-0.38666	0.39620	0.08641
				10	0.27199	0.30649	0.14127
				11	-0.27102	0.30146	0.13200
				12	0.89204	1.46385	1.16066
				13	-0.37801	0.38306	0.06201
				14	-0.30943	0.32582	0.10203
				15	0.21075	0.28262	0.18829
				16	-0.18408	0.20378	0.08740
				17	-0.29219	0.32124	0.13349
				18	0.08910	0.18301	0.15985

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR     ERROR                  MN   ERROR   RMS  ERROR    STD    DEV

   23        43  0.16568  0.22497
                                                1    -0.18125      0.25714      0.18240
                                                2    -0.30597      0.36488      0.19879
                                                3    -0.24156      0.31117      0.19616
                                                4    -0.37085      0.41344      0.18276
                                                5     0.69771      1.56902      1.40535
                                                6    -0.06367      0.25155      0.24336
                                                7     1.35202      1.60640      0.86751
                                                8     0.34708      0.48791      0.34292
                                                9    -0.29668      0.43660      0.32031
                                               10     0.84256      0.90631      0.33389
                                               11     0.15961      0.58427      0.56204
                                               12     2.22737      2.64967      1.43512
                                               13    -0.18614      0.25278      0.17101
                                               14     0.01385      0.25449      0.25411
                                               15     0.63976      0.73579      0.36344
                                               16     0.03269      0.24511      0.24292
                                               17     0.20118      0.34736      0.28317
                                               18     0.32429      0.40295      0.23916
```

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
24	26	0.13086	0.14940				
				1	-0.27254	0.32580	0.17852
				2	-0.39397	0.42247	0.15254
				3	-0.32916	0.36775	0.16398
				4	-0.45523	0.47640	0.14046
				5	0.90332	1.84685	1.61086
				6	-0.19113	0.29717	0.22755
				7	0.97370	1.14877	0.60957
				8	0.22151	0.36872	0.29476
				9	-0.34462	0.43404	0.26386
				10	0.68160	0.77737	0.37379
				11	-0.00900	0.46079	0.46071
				12	1.94318	2.38780	1.38768
				13	-0.26386	0.31767	0.17689
				14	-0.11288	0.23065	0.20114
				15	0.43842	0.58379	0.38548
				16	-0.07700	0.23842	0.22564
				17	0.08314	0.32851	0.31782
				18	0.26654	0.43052	0.33809

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
25	62	0.06146	0.06147				
				1	-0.03668	0.24030	0.23748
				2	-0.18689	0.31596	0.25476
				3	-0.10380	0.27617	0.25593
				4	-0.26766	0.35167	0.22811
				5	1.18448	1.98046	1.58721
				6	0.08610	0.32092	0.30915
				7	1.84388	2.19309	1.18732
				8	0.61178	0.76463	0.45868
				9	-0.13658	0.39366	0.36921
				10	1.22678	1.43412	0.74279
				11	0.28990	0.52193	0.43401
				12	3.04903	3.38575	1.47199
				13	-0.04060	0.22402	0.22031
				14	0.23418	0.57192	0.52178
				15	0.94185	1.06306	0.49296
				16	0.23551	0.41444	0.34103
				17	0.49355	0.89937	0.75185
				18	0.61639	0.86749	0.61041

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION   CORRELATION   CORRELATION
                   ERROR     ERROR                  MN   ERROR    RMS ERROR     STD    DEV

   26        23  0.06360   0.06417
                                               1      0.13826       0.23117       0.18526
                                               2     -0.12107       0.18873       0.14478
                                               3     -0.03084       0.15701       0.15395
                                               4     -0.18140       0.22674       0.13603
                                               5      1.82271       2.70248       1.99528
                                               6      0.49798       0.65371       0.42350
                                               7      1.67303       1.91893       0.93981
                                               8      0.71368       0.76579       0.27765
                                               9     -0.40064       0.59876       0.44497
                                              10      1.13018       1.13809       0.13397
                                              11      1.29625       1.73400       1.15172
                                              12      3.93282       4.29037       1.71470
                                              13      0.12854       0.21843       0.17660
                                              14      0.07853       0.18077       0.16282
                                              15      1.40377       1.48737       0.49163
                                              16      0.35562       0.41968       0.22286
                                              17      0.14316       0.20021       0.13996
                                              18      0.51274       0.53323       0.14637
```

```
DATA SET  POINTS  DATA MN  DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR    ERROR                  MN   ERROR   RMS  ERROR   STD    DEV

   27       18  0.06177  0.06177
                                               1     0.11993      0.16808      0.11775
                                               2    -0.10548      0.15935      0.11945
                                               3    -0.00225      0.12297      0.12295
                                               4    -0.18573      0.21214      0.10251
                                               5     2.19116      3.08366      2.16974
                                               6     0.33666      0.45863      0.31146
                                               7     1.92933      2.09533      0.81737
                                               8     0.81177      0.84771      0.24422
                                               9    -0.17366      0.44512      0.40985
                                              10     1.30194      1.33532      0.29670
                                              11     0.83167      1.18793      0.84824
                                              12     3.96880      4.26627      1.56515
                                              13     0.11788      0.16077      0.10931
                                              14     0.16719      0.31766      0.27010
                                              15     1.30270      1.33536      0.29353
                                              16     0.39852      0.43496      0.17426
                                              17     0.29533      0.49211      0.39364
                                              18     0.66240      0.72868      0.30365
```

```
DATA SET  POINTS  DATA MN  DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR    ERROR                  MN   ERROR   RMS ERROR    STD    DEV

    28        36  0.09903  0.12133
                                               1    -0.28460      0.31060      0.12440
                                               2    -0.43498      0.45247      0.12458
                                               3    -0.36531      0.38825      0.13149
                                               4    -0.48437      0.49672      0.11006
                                               5     1.15766      1.85854      1.45396
                                               6    -0.14988      0.24215      0.19020
                                               7     0.89323      1.14453      0.71560
                                               8     0.13416      0.26630      0.23004
                                               9    -0.48851      0.56156      0.27696
                                              10     0.64324      0.67022      0.18824
                                              11     0.17268      0.46421      0.43090
                                              12     2.52628      2.77890      1.15767
                                              13    -0.28503      0.30888      0.11901
                                              14    -0.14908      0.25189      0.20304
                                              15     0.50153      0.57644      0.28821
                                              16    -0.10263      0.20914      0.18222
                                              17     0.06569      0.24985      0.24106
                                              18     0.22146      0.28069      0.17245
```

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
29	44	0.06178	0.06178				
				1	-0.14543	0.26528	0.22187
				2	-0.32475	0.38861	0.21343
				3	-0.24238	0.33694	0.23405
				4	-0.38326	0.42505	0.18380
				5	1.57470	2.26480	1.62777
				6	0.01784	0.28590	0.28534
				7	1.27705	1.68491	1.09911
				8	0.34775	0.55081	0.42716
				9	-0.39552	0.55711	0.39235
				10	0.96106	1.20355	0.72449
				11	0.44469	0.77643	0.63647
				12	3.19793	3.48912	1.39542
				13	-0.15153	0.26215	0.21391
				14	0.03245	0.48399	0.48290
				15	0.80458	0.93541	0.47712
				16	0.06773	0.34117	0.33438
				17	0.31003	0.81137	0.74981
				18	0.46897	0.82852	0.68301

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR     ERROR                  MN  ERROR    RMS ERROR    STD   DEV

   30        13  0.06165   0.06165
                                                1    -0.14772      0.28724      0.24634
                                                2    -0.32387      0.40535      0.24376
                                                3    -0.24019      0.36040      0.26870
                                                4    -0.38425      0.43457      0.20298
                                                5     1.78797      2.30227      1.45039
                                                6    -0.01086      0.29217      0.29197
                                                7     1.30640      1.74590      1.15824
                                                8     0.37968      0.63390      0.50762
                                                9    -0.39642      0.57767      0.42018
                                               10     1.23561      1.50562      0.86032
                                               11     0.37218      0.46086      0.27181
                                               12     3.12171      3.34926      1.21345
                                               13    -0.15496      0.28860      0.24346
                                               14     0.16782      0.65720      0.63541
                                               15     0.77938      0.92254      0.49361
                                               16     0.07771      0.38969      0.38187
                                               17     0.71112      1.21857      0.98955
                                               18     0.91295      1.19317      0.76823
```

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR     ERROR                  MN  ERROR    RMS ERROR     STD   DEV

   31       12   0.06172   0.06172
                                            1       -0.09942      0.14214      0.10158
                                            2       -0.29973      0.31592      0.09983
                                            3       -0.21101      0.24211      0.11871
                                            4       -0.35664      0.36524      0.07876
                                            5        2.18439      2.87395      1.86763
                                            6        0.06978      0.17316      0.15848
                                            7        1.29874      1.45600      0.65819
                                            8        0.42673      0.48675      0.23415
                                            9       -0.42726      0.51689      0.29090
                                           10        0.74365      0.76416      0.17582
                                           11        0.55936      0.75048      0.50034
                                           12        3.93054      4.19002      1.45160
                                           13       -0.10639      0.14826      0.10326
                                           14       -0.13031      0.18619      0.13300
                                           15        0.88710      0.91597      0.22816
                                           16        0.11688      0.20922      0.17352
                                           17       -0.08804      0.16238      0.13644
                                           18        0.25049      0.26170      0.07577
```

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR     ERROR                  MN   ERROR   RMS  ERROR    STD    DEV

    32        35  0.09475   0.10437
                                                1   -0.32343      0.36770      0.17492
                                                2   -0.47330      0.49143      0.13228
                                                3   -0.40676      0.43187      0.14511
                                                4   -0.51684      0.53215      0.12675
                                                5    1.21475      1.92084      1.48796
                                                6   -0.19294      0.34880      0.29057
                                                7    0.72037      0.93332      0.59341
                                                8    0.05744      0.25036      0.24368
                                                9   -0.54880      0.59679      0.23448
                                               10    0.53007      0.60085      0.28292
                                               11    0.16167      0.61251      0.59079
                                               12    2.40917      2.77917      1.38553
                                               13   -0.32351      0.36467      0.16830
                                               14   -0.22885      0.27943      0.16034
                                               15    0.42851      0.60692      0.42980
                                               16   -0.15987      0.26608      0.21269
                                               17   -0.03682      0.19409      0.19057
                                               18    0.12854      0.24145      0.20438
```

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR     ERROR                   MN   ERROR   RMS  ERROR   STD    DEV

   33         6  0.15038  0.18285
                                                1     0.52013      0.80017      0.60806
                                                2     0.37649      0.70424      0.59516
                                                3     0.47835      0.77399      0.60848
                                                4     0.22575      0.58545      0.54017
                                                5     0.44867      0.78030      0.63840
                                                6     0.68551      0.85462      0.51035
                                                7     4.04231      4.50706      1.99331
                                                8     1.75148      2.09609      1.15148
                                                9     0.57284      0.86511      0.64827
                                               10     2.27614      2.68670      1.42743
                                               11     0.62326      0.85840      0.59025
                                               12     4.43502      4.61172      1.26434
                                               13     0.49963      0.77880      0.59741
                                               14     0.86650      1.20275      0.83414
                                               15     1.93766      2.21019      1.06323
                                               16     1.00889      1.26489      0.76294
                                               17     0.79705      1.15994      0.84272
                                               18     1.37267      1.76232      1.10524
```

Appendix E

CORRELATION EVALUATION FOR ADIABATIC DATA BASED ON FLOW CONDITIONS

The property ranges of all of the sets are given in table 6.8. The flow conditions ranges are also identified for each data set.

These results were obtained using the Thom void fraction correlation and the smooth tube single-phase friction factor to reduce the data.

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR     ERROR                  MN  ERROR    RMS ERROR    STD   DEV

    1        20  0.46834   1.47052
                                            1       0.03212      1.12889      1.12844
                                            2      -0.02882      1.10375      1.10337
                                            3       0.02006      1.12380      1.12362
                                            4      -0.15538      1.03783      1.02613
                                            5       0.04537      1.19399      1.19313
                                            6       0.06513      1.15116      1.14932
                                            7       1.68805      3.29947      2.83496
                                            8       0.73767      1.98893      1.84708
                                            9       0.28492      1.21238      1.17842
                                           10       1.48314      3.14828      2.77704
                                           11      -0.08444      1.13193      1.12877
                                           12       0.25044      0.75261      0.70972
                                           13       0.07430      1.18347      1.18114
                                           14       0.48852      1.54622      1.46702
                                           15       0.77679      1.91955      1.75536
                                           16       0.29042      1.34942      1.31780
                                           17       0.94436      2.39814      2.20437
                                           18       1.03440      2.74512      2.54277
```

Pressure 250-900 psia
Mass Velocity $0\text{-}1\mathrm{x}10^6 \mathrm{lbm/hr\text{-}ft}^2$
Quality 0-.1
Points 20

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
2	30	0.10329	0.13621				
				1	-0.21577	0.25013	0.12652
				2	-0.26945	0.29724	0.12551
				3	-0.22637	0.25927	0.12639
				4	-0.37580	0.39575	0.12404
				5	-0.21280	0.25305	0.13693
				6	-0.18781	0.22706	0.12760
				7	1.03001	1.09926	0.38402
				8	0.31916	0.38676	0.21845
				9	0.02471	0.27203	0.27091
				10	0.65817	0.72202	0.29685
				11	-0.32685	0.35861	0.14753
				12	0.60329	0.90045	0.66847
				13	-0.17977	0.22478	0.13494
				14	-0.01577	0.17706	0.17636
				15	0.37917	0.43249	0.20804
				16	-0.00596	0.14904	0.14892
				17	-0.06047	0.21148	0.20265
				18	0.18424	0.31290	0.25290

Pressure	250-900 psia
Mass Velocity	1 - 2×10^6 lbm/hr-ft^2
Quality	0-.1
Points	30

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
3	13	0.05655	0.05683				
				1	-0.28828	0.32617	0.15259
				2	-0.33350	0.35944	0.13405
				3	-0.29835	0.33312	0.14818
				4	-0.41167	0.42594	0.10930
				5	-0.29724	0.32708	0.13651
				6	-0.25640	0.31476	0.18258
				7	1.06605	1.19707	0.54453
				8	0.27542	0.41231	0.30684
				9	-0.19453	0.27523	0.19470
				10	0.41127	0.54175	0.35263
				11	-0.32091	0.34774	0.13394
				12	0.44910	0.99031	0.88262
				13	-0.26957	0.31324	0.15954
				14	-0.28601	0.33679	0.17782
				15	0.27710	0.43669	0.33752
				16	-0.09353	0.23980	0.22081
				17	-0.32128	0.35021	0.13939
				18	-0.12017	0.16967	0.11978

Pressure	250-900 psia
Mass Velocity	$2\text{-}3\times10^{6}$ lbm/hr-ft^{2}
Quality	0-.1
Points	13

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
4	67	0.24001	0.39115				
				1	-0.17530	0.34589	0.29818
				2	-0.21555	0.35548	0.28268
				3	-0.18518	0.34760	0.29417
				4	-0.28029	0.38276	0.26065
				5	-0.16185	0.34128	0.30046
				6	-0.18194	0.36106	0.31186
				7	1.50046	1.80210	0.99809
				8	0.45695	0.70372	0.53518
				9	-0.15074	0.34153	0.30646
				10	1.01794	1.31816	0.83745
				11	-0.14444	0.34553	0.31390
				12	-0.16798	0.97035	0.95570
				13	-0.20042	0.35193	0.28929
				14	0.15419	0.51306	0.48934
				15	0.42305	0.68859	0.54331
				16	0.02149	0.37741	0.37680
				17	0.32706	0.74627	0.67079
				18	0.64097	0.92183	0.66252

Pressure	900-1500 psia
Mass Velocity	$0\text{-}1\times10^{6}$ lbm/hr-ft^{2}
Quality	0-.1
Points	67

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
5	107	0.10789	0.13795				
				1	-0.12339	0.23779	0.20327
				2	-0.16592	0.25749	0.19690
				3	-0.13387	0.24196	0.20156
				4	-0.23383	0.29934	0.18689
				5	-0.11057	0.23836	0.21117
				6	-0.13268	0.23597	0.19513
				7	1.63735	1.78950	0.72208
				8	0.53572	0.64909	0.36651
				9	-0.09775	0.22754	0.20547
				10	0.78774	0.90448	0.44446
				11	-0.08951	0.23323	0.21537
				12	0.37031	1.06545	0.99902
				13	-0.14749	0.24460	0.19512
				14	0.02703	0.25290	0.25146
				15	0.50499	0.62803	0.37337
				16	0.08329	0.26488	0.25144
				17	0.02174	0.25696	0.25604
				18	0.44543	0.55813	0.33630

Pressure	900-1500 psia
Mass Velocity	1-2x10^{6}lbm/hr-ft^2
Quality	0-.1
Points	107

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
6	84	0.06843	0.07692				
				1	-0.15984	0.22715	0.16140
				2	-0.19724	0.25243	0.15754
				3	-0.16885	0.23286	0.16035
				4	-0.26046	0.30122	0.15131
				5	-0.14239	0.21957	0.16713
				6	-0.16938	0.23977	0.16971
				7	1.46205	1.56475	0.55755
				8	0.47115	0.55274	0.28902
				9	-0.13341	0.21242	0.16530
				10	0.49846	0.58240	0.30121
				11	-0.13017	0.21332	0.16900
				12	0.45902	0.94706	0.82838
				13	-0.18331	0.24202	0.15802
				14	-0.20515	0.25828	0.15692
				15	0.41622	0.50755	0.29046
				16	0.02856	0.19899	0.19693
				17	-0.18406	0.24665	0.16418
				18	0.13436	0.29190	0.25914

Pressure	900-1500 psia
Mass Velocity	$2\text{-}3\text{x}10^6$ lbm/hr-ft^2
Quality	0-.1
Points	84

```
DATA SET   POINTS  DATA MN   DATA RMS   CORRELATION   CORRELATION    CORRELATION    CORRELATION
                    ERROR     ERROR                    MN   ERROR     RMS ERROR      STD    DEV

     7        42   0.07608   0.08562
                                                 1     -0.27316        0.31583        0.15853
                                                 2     -0.37461        0.39837        0.13554
                                                 3     -0.29810        0.33525        0.15340
                                                 4     -0.48197        0.49466        0.11131
                                                 5      0.61510        1.79343        1.68465
                                                 6     -0.29334        0.41475        0.29320
                                                 7      0.89954        1.01191        0.46346
                                                 8      0.22466        0.34654        0.26385
                                                 9      0.13934        0.49775        0.47785
                                                10      0.75624        0.85238        0.39328
                                                11     -0.35127        0.37923        0.14291
                                                12      1.30960        1.54192        0.81391
                                                13     -0.24276        0.29404        0.16590
                                                14      0.12851        0.27689        0.24527
                                                15      0.37681        0.47385        0.28732
                                                16     -0.02679        0.20821        0.20647
                                                17      0.43726        0.62401        0.44519
                                                18      0.29350        0.41672        0.29583
```

Pressure	250-900 psia
Mass Velocity	0-1x10^6lbm/hr-ft^2
Quality	0-.1
Points	42

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
8	37	0.05944	0.06016				
				1	-0.04318	0.32949	0.32665
				2	-0.18329	0.31518	0.25640
				3	-0.07587	0.32174	0.31256
				4	-0.33595	0.38306	0.18406
				5	2.61929	4.61033	3.79400
				6	-0.26065	0.34455	0.22533
				7	1.29374	1.34605	0.37162
				8	0.54178	0.66971	0.39368
				9	0.71041	1.27982	1.06454
				10	0.95649	1.10140	0.54609
				11	-0.19689	0.27790	0.19612
				12	2.37677	2.68458	1.24819
				13	-0.01341	0.32331	0.32304
				14	0.16148	0.37966	0.34361
				15	0.75713	0.90563	0.49690
				16	0.27248	0.49781	0.41662
				17	0.04491	0.31799	0.31480
				18	0.27174	0.47031	0.38386

Pressure	250-900 psia
Mass Velocity	1-2x10^6 lbm/hr-ft^2
Quality	.1-.2
Points	37

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
9	8	0.05760	0.05761				
				1	-0.05663	0.07518	0.04944
				2	-0.18141	0.18783	0.04868
				3	-0.08980	0.10182	0.04800
				4	-0.30481	0.30840	0.04694
				5	-0.12666	0.14169	0.06350
				6	0.15974	0.17823	0.07905
				7	1.75973	1.77847	0.25754
				8	0.68339	0.69016	0.09644
				9	0.20347	0.21622	0.07315
				10	0.89797	0.90265	0.09179
				11	-0.08507	0.10851	0.06736
				12	2.60073	2.63040	0.39396
				13	-0.00938	0.04378	0.04276
				14	-0.06053	0.10322	0.08361
				15	0.86174	0.86773	0.10182
				16	0.27771	0.28647	0.07031
				17	-0.17356	0.18430	0.06197
				18	0.01497	0.08544	0.08412

Pressure	250-900 psia
Mass Velocity	$2\text{-}3\text{x}10^6$lbm/hr-ft^2
Quality	.1-.2
Points	8

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
10	86	0.10106	0.13306				
				1	-0.25063	0.30308	0.17041
				2	-0.32895	0.36387	0.15555
				3	-0.27353	0.31972	0.16552
				4	-0.40565	0.42986	0.14222
				5	-0.31219	0.34926	0.15659
				6	-0.10958	0.22561	0.19721
				7	1.60911	1.74339	0.67097
				8	0.33583	0.43813	0.28138
				9	-0.23407	0.28125	0.15592
				10	0.85126	0.96190	0.44790
				11	-0.18872	0.27513	0.20021
				12	1.33269	1.60590	0.89602
				13	-0.25830	0.30520	0.16257
				14	0.13415	0.32172	0.29241
				15	0.50075	0.61372	0.35484
				16	0.01301	0.22909	0.22872
				17	0.24707	0.48395	0.41613
				18	0.36307	0.45989	0.28228

Pressure	900-1500 psia
Mass Velocity	$0\text{-}1\text{x}10^{6}$ lbm/hr-ft^{2}
Quality	.1-.2
Points	86

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
11	143	0.06779	0.07564				
				1	-0.16778	0.26820	0.20925
				2	-0.25692	0.32063	0.19182
				3	-0.19408	0.28171	0.20419
				4	-0.34240	0.38317	0.17200
				5	-0.23307	0.30642	0.19893
				6	-0.00146	0.23911	0.23911
				7	1.88900	2.03098	0.74604
				8	0.48280	0.61125	0.37487
				9	-0.14949	0.26068	0.21356
				10	0.73087	0.86577	0.46410
				11	-0.09708	0.24824	0.22847
				12	2.00699	2.23773	0.98965
				13	-0.17641	0.27130	0.20611
				14	0.00868	0.27778	0.27765
				15	0.67044	0.78817	0.41439
				16	0.12645	0.30579	0.27842
				17	-0.05129	0.29026	0.28569
				18	0.24651	0.40827	0.32545

Pressure	900-1500 psia
Mass Velocity	1-2x10^6lbm/hr-ft^2
Quality	.1-.2
Points	143

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR     ERROR                  MN  ERROR    RMS ERROR    STD    DEV

    12        90  0.05777   0.05795
                                              1     -0.06059      0.17764      0.16698
                                              2     -0.16130      0.21961      0.14903
                                              3     -0.08999      0.18481      0.16142
                                              4     -0.25928      0.29113      0.13240
                                              5     -0.13070      0.20446      0.15723
                                              6      0.12890      0.25252      0.21714
                                              7      2.23721      2.31351      0.58925
                                              8      0.68442      0.74608      0.29698
                                              9     -0.03070      0.17341      0.17067
                                             10      0.70959      0.76982      0.29850
                                             11      0.01220      0.18572      0.18532
                                             12      2.63966      2.79457      0.91749
                                             13     -0.06763      0.17822      0.16488
                                             14     -0.13431      0.20524      0.15519
                                             15      0.87949      0.94326      0.34093
                                             16      0.27199      0.35460      0.22751
                                             17     -0.16692      0.22250      0.14711
                                             18      0.12595      0.19561      0.14966
```

Pressure	900-1500 psia
Mass Velocity	$2\text{-}3\times10^{6}$ lbm/hr-ft^{2}
Quality	.1-.2
Points	90

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
13	29	0.05845	0.05851				
				1	-0.21054	0.31916	0.23986
				2	-0.36737	0.40692	0.17499
				3	-0.25686	0.34047	0.22348
				4	-0.47021	0.48902	0.13432
				5	2.09199	3.12941	2.32739
				6	-0.42166	0.46798	0.20299
				7	0.83018	0.89465	0.33345
				8	0.26352	0.39500	0.29425
				9	0.42686	0.99545	0.89928
				10	0.79269	0.88817	0.40060
				11	-0.20631	0.27983	0.18906
				12	2.03060	2.29409	1.06747
				13	-0.19531	0.30581	0.23532
				14	0.06701	0.26096	0.25221
				15	0.47472	0.59308	0.35551
				16	0.03079	0.29147	0.28984
				17	0.34069	0.50767	0.37638
				18	0.27787	0.42205	0.31766

Pressure	250-900 psia
Mass Velocity	0-1x10^{6}lbm/hr-ft^2
Quality	.2-.3
Points	29

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
14	28	0.05783	0.05789				
				1	0.01629	0.40367	0.40334
				2	-0.17939	0.35176	0.30259
				3	-0.04021	0.38168	0.37956
				4	-0.31534	0.38979	0.22912
				5	3.62435	5.60428	4.27458
				6	-0.25237	0.34236	0.23135
				7	1.38100	1.44556	0.42717
				8	0.63933	0.80886	0.49549
				9	0.81237	1.58957	1.36630
				10	1.06805	1.27411	0.69471
				11	0.00230	0.29327	0.29326
				12	3.28060	3.64726	1.59381
				13	0.04115	0.39712	0.39498
				14	0.11777	0.43201	0.41565
				15	0.90614	1.08733	0.60100
				16	0.33481	0.60071	0.49875
				17	0.05525	0.40453	0.40074
				18	0.28316	0.55662	0.47921

Pressure	250-900 psia
Mass Velocity	1-2x10^{6}lbm/hr-ft^2
Quality	.2-.3
Points	28

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
15	9	0.05739	0.05739				
				1	0.04649	0.07561	0.05963
				2	-0.13784	0.14520	0.04565
				3	-0.01267	0.05404	0.05253
				4	-0.25843	0.26208	0.04354
				5	2.11459	2.68620	1.65656
				6	-0.10851	0.30815	0.28842
				7	1.93268	1.94659	0.23227
				8	0.82495	0.83078	0.09818
				9	0.28457	0.29681	0.08438
				10	1.04353	1.04801	0.09677
				11	0.14801	0.18388	0.10910
				12	3.86981	3.91224	0.57462
				13	0.08674	0.10392	0.05724
				14	-0.11109	0.12444	0.05608
				15	1.10574	1.11303	0.12716
				16	0.39881	0.40581	0.07508
				17	-0.12214	0.13270	0.05186
				18	0.07023	0.09835	0.06885

Pressure	250-900 psia
Mass Velocity	2-3x10^6 lbm/hr-ft^2
Quality	.2-.3
Points	9

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
16	80	0.07519	0.09040				
				1	-0.24127	0.30291	0.18315
				2	-0.35507	0.38930	0.15964
				3	-0.28077	0.33100	0.17529
				4	-0.42838	0.45140	0.14229
				5	-0.34862	0.38594	0.16556
				6	0.00710	0.24084	0.24073
				7	1.56620	1.70405	0.67142
				8	0.30217	0.43556	0.31369
				9	-0.27413	0.32811	0.18031
				10	0.83115	1.00760	0.56960
				11	-0.09697	0.23754	0.21684
				12	2.18929	2.44441	1.08726
				13	-0.25542	0.31143	0.17818
				14	0.08652	0.38421	0.37434
				15	0.58824	0.70410	0.38694
				16	0.02880	0.25245	0.25080
				17	0.26576	0.67943	0.62529
				18	0.33403	0.62204	0.52475

Pressure	900-1500 psia
Mass Velocity	0-1x10^{6}lbm/hr-ft^{2}
Quality	.2-.3
Points	79

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
17	98	0.05833	0.05841				
				1	-0.15500	0.21005	0.14177
				2	-0.28630	0.31035	0.11979
				3	-0.20074	0.24126	0.13383
				4	-0.36903	0.38404	0.10633
				5	-0.28053	0.30680	0.12421
				6	0.12460	0.22845	0.19148
				7	1.79624	1.86033	0.48410
				8	0.45794	0.51846	0.24308
				9	-0.18102	0.22765	0.13805
				10	0.68385	0.73133	0.25920
				11	0.00690	0.17808	0.17794
				12	2.90740	3.03938	0.88590
				13	-0.16707	0.21744	0.13917
				14	-0.09209	0.17221	0.14552
				15	0.76203	0.81909	0.30036
				16	0.14329	0.23921	0.19155
				17	-0.10898	0.18165	0.14532
				18	0.19907	0.25419	0.15807

Pressure	900-1500 psia
Mass Velocity	$1\text{-}2\times10^{6}$ lbm/hr-ft^{2}
Quality	.2-.3
Points	95

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
18	76	0.05688	0.05693				
				1	0.09372	0.16827	0.13975
				2	-0.07414	0.13732	0.11559
				3	0.03579	0.13509	0.13026
				4	-0.18207	0.20953	0.10369
				5	-0.06173	0.13093	0.11547
				6	0.45392	0.49235	0.19070
				7	2.62611	2.66942	0.47887
				8	0.89134	0.92115	0.23244
				9	0.06687	0.14298	0.12638
				10	0.92119	0.94797	0.22372
				11	0.29471	0.35033	0.18941
				12	4.40027	4.50287	0.95574
				13	0.07857	0.15725	0.13621
				14	-0.13669	0.17034	0.10165
				15	1.27670	1.31194	0.30204
				16	0.48189	0.51657	0.18607
				17	-0.07752	0.13579	0.11149
				18	0.24191	0.28746	0.15528

Pressure	900-1500 psia
Mass Velocity	2-3x10^6lbm/hr-ft^2
Quality	.2-.3
Points	76

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
19	34	0.05739	0.05740				
				1	-0.16541	0.30188	0.25253
				2	-0.36307	0.40271	0.17424
				3	-0.23593	0.32913	0.22949
				4	-0.45114	0.47207	0.13902
				5	2.80123	3.38261	1.89608
				6	-0.36241	0.40009	0.16949
				7	0.80526	0.85296	0.28123
				8	0.31225	0.43554	0.30363
				9	0.38669	1.02410	0.94828
				10	0.84136	0.93219	0.40136
				11	-0.00532	0.24100	0.24094
				12	2.64083	2.86490	1.11072
				13	-0.14820	0.28523	0.24371
				14	0.00673	0.21713	0.21702
				15	0.57166	0.67468	0.35833
				16	0.04704	0.29417	0.29039
				17	0.23344	0.41419	0.34214
				18	0.26091	0.41284	0.31995

Pressure	250-900 psia
Mass Velocity	0-1x10^6lbm/hr-ft^2
Quality	.3-.4
Points	34

```
DATA SET   POINTS   DATA MN   DATA RMS   CORRELATION   CORRELATION   CORRELATION   CORRELATION
                     ERROR     ERROR                    MN  ERROR     RMS ERROR     STD   DEV

    20         31  0.05781   0.05790
                                                  1     -0.11632       0.20089       0.16379
                                                  2     -0.31246       0.33493       0.12061
                                                  3     -0.19103       0.24414       0.15203
                                                  4     -0.39778       0.40928       0.09634
                                                  5      3.25894       3.63182       1.60293
                                                  6     -0.29846       0.31658       0.10555
                                                  7      1.18276       1.21196       0.26446
                                                  8      0.47138       0.52212       0.22451
                                                  9      0.06629       0.54436       0.54030
                                                 10      0.82252       0.87988       0.31250
                                                 11      0.11681       0.19663       0.15818
                                                 12      3.35818       3.44254       0.75742
                                                 13     -0.07947       0.18529       0.16739
                                                 14     -0.08882       0.19571       0.17440
                                                 15      0.77000       0.81328       0.26179
                                                 16      0.12756       0.23678       0.19948
                                                 17     -0.10810       0.21386       0.18453
                                                 18      0.09953       0.21044       0.18541
```

Pressure	250-900 psia
Mass Velocity	$1\text{-}2\times10^{6}$ lbm/hr-ft^{2}
Quality	.3-.4
Points	31

```
DATA SET  POINTS  DATA MN   DATA RMS   CORRELATION  CORRELATION  CORRELATION  CORRELATION
                  ERROR     ERROR                   MN   ERROR   RMS ERROR    STD    DEV

    21         9  0.05744   0.05744
                                                1     0.10086      0.10460      0.02771
                                                2    -0.13562      0.13785      0.02468
                                                3     0.01211      0.02692      0.02404
                                                4    -0.24334      0.24455      0.02431
                                                5     3.58919      3.65645      0.69814
                                                6    -0.14509      0.15838      0.06350
                                                7     1.81140      1.82285      0.20399
                                                8     0.86058      0.86169      0.04361
                                                9     0.27438      0.29342      0.10397
                                               10     1.09933      1.10086      0.05808
                                               11     0.37394      0.38264      0.08114
                                               12     4.58321      4.60599      0.45752
                                               13     0.14953      0.15291      0.03195
                                               14    -0.14791      0.15280      0.03834
                                               15     1.22358      1.22521      0.06325
                                               16     0.41582      0.41757      0.03820
                                               17    -0.10326      0.10976      0.03721
                                               18     0.09169      0.10582      0.05282
```

Pressure	250-900 psia
Mass Velocity	2-3x10^{6}lbm-hr-ft^2
Quality	.3-.4
Points	9

```
DATA SET  POINTS  DATA MN  DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                  ERROR    ERROR                  MN   ERROR   RMS ERROR    STD    DEV

   22       68   0.06788  0.07084
                                          1       -0.24717      0.29520      0.16140
                                          2       -0.39073      0.41255      0.13239
                                          3       -0.30597      0.34048      0.14936
                                          4       -0.45329      0.46878      0.11953
                                          5        1.21005      1.75294      1.26830
                                          6       -0.26835      0.36447      0.24662
                                          7        1.32921      1.43619      0.54391
                                          8        0.25155      0.36580      0.26558
                                          9       -0.36306      0.38959      0.14133
                                         10        0.79632      0.92437      0.46939
                                         11        0.01458      0.22386      0.22339
                                         12        2.74678      2.92869      1.01608
                                         13       -0.25901      0.30292      0.15708
                                         14        0.00683      0.26889      0.26880
                                         15        0.60182      0.69767      0.35293
                                         16       -0.01369      0.21328      0.21284
                                         17        0.22176      0.53068      0.48213
                                         18        0.31756      0.51884      0.41031
```

Pressure	900-1500 psia
Mass Velocity	0-1x10^6lbm/hr-ft^2
Quality	.3-.4
Points	68

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
23	90	0.05831	0.05834				
				1	-0.06169	0.15369	0.14076
				2	-0.24363	0.26971	0.11571
				3	-0.13694	0.18866	0.12977
				4	-0.32086	0.33777	0.10551
				5	2.03997	2.38663	1.23877
				6	-0.12434	0.27163	0.24150
				7	1.86800	1.93335	0.49839
				8	0.55820	0.60249	0.22674
				9	-0.21062	0.24164	0.11843
				10	0.79024	0.82130	0.22373
				11	0.27453	0.34316	0.20588
				12	3.94935	4.09506	1.08268
				13	-0.07517	0.15470	0.13521
				14	-0.06803	0.14585	0.12901
				15	0.99382	1.04320	0.31714
				16	0.22580	0.29204	0.18521
				17	-0.06623	0.15188	0.13668
				18	0.26250	0.29496	0.13452

Pressure	900-1500 psia
Mass Velocity	$1\text{-}2 \times 10^6$ lbm/hr-ft^2
Quality	.3-.4
Points	90

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
24	63	0.05675	0.05680				
				1	0.22387	0.48379	0.42888
				2	-0.01054	0.35042	0.35026
				3	0.12832	0.41388	0.39349
				4	-0.11312	0.34001	0.32064
				5	3.03259	3.33185	1.38009
				6	0.14631	0.67097	0.65482
				7	2.76043	3.12566	1.46623
				8	1.04054	1.24383	0.68146
				9	0.04646	0.29391	0.29022
				10	1.07248	1.25097	0.64399
				11	0.64403	0.89619	0.62321
				12	5.73997	6.27025	2.52364
				13	0.20690	0.45883	0.40953
				14	-0.13116	0.33167	0.30463
				15	1.59512	1.86412	0.96466
				16	0.60302	0.82395	0.56148
				17	0.00334	0.36609	0.36607
				18	0.35268	0.51437	0.37443

Pressure	900-1500 psia
Mass Velocity	$2\text{-}3\times10^{6}$ lbm/hr-ft^{2}
Quality	.3-.4
Points	63

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
25	28	0.05784	0.05792				
				1	-0.24947	0.29658	0.16038
				2	-0.44278	0.45530	0.10603
				3	-0.33195	0.36022	0.13989
				4	-0.50453	0.51259	0.09057
				5	2.24906	2.52905	1.15665
				6	-0.31611	0.34624	0.14126
				7	0.59844	0.64776	0.24791
				8	0.18665	0.27809	0.20615
				9	-0.06277	0.56016	0.55664
				10	0.69414	0.74585	0.27288
				11	0.05876	0.21588	0.20773
				12	2.50914	2.63026	0.78896
				13	-0.22451	0.27248	0.15440
				14	-0.13750	0.19267	0.13497
				15	0.45941	0.51887	0.24119
				16	-0.07670	0.19429	0.17851
				17	0.14070	0.31258	0.27912
				18	0.16893	0.27505	0.21706

Pressure	250-900 psia
Mass Velocity	$0\text{-}1\text{x}10^6 \text{lbm/hr-ft}^2$
Quality	.4-.5
Points	28

```
DATA SET   POINTS   DATA MN    DATA RMS   CORRELATION   CORRELATION   CORRELATION   CORRELATION
                     ERROR      ERROR                    MN   ERROR    RMS ERROR     STD    DEV

    26        17   0.05707    0.05708
                                                    1      -0.09237       0.12442       0.08335
                                                    2      -0.31806       0.32362       0.05972
                                                    3      -0.19329       0.20648       0.07260
                                                    4      -0.38776       0.39143       0.05349
                                                    5       2.60825       2.76244       0.91002
                                                    6      -0.14413       0.17074       0.09155
                                                    7       1.08547       1.10045       0.18091
                                                    8       0.47310       0.49156       0.13346
                                                    9      -0.12481       0.18245       0.13308
                                                   10       0.80537       0.81605       0.13155
                                                   11       0.33295       0.36191       0.14186
                                                   12       3.63494       3.67119       0.51461
                                                   13      -0.05262       0.10763       0.09390
                                                   14      -0.15689       0.16659       0.05603
                                                   15       0.83559       0.85157       0.16419
                                                   16       0.12923       0.16332       0.09987
                                                   17      -0.14953       0.16161       0.06131
                                                   18       0.06081       0.08685       0.06202
```

Pressure	250-900 psia
Mass Velocity	$1\text{-}2\times10^{6}$ lbm/hr-ft^{2}
Quality	.4-.5
Points	17

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
27	9	0.05727	0.05727				
				1	0.13993	0.14054	0.01299
				2	-0.13887	0.13938	0.01191
				3	0.01555	0.02142	0.01473
				4	-0.22655	0.22674	0.00944
				5	3.67709	3.75155	0.74370
				6	0.07619	0.08928	0.04653
				7	1.68453	1.68761	0.10197
				8	0.85308	0.85358	0.02939
				9	0.07360	0.13361	0.11151
				10	1.07427	1.07550	0.05155
				11	0.67001	0.67288	0.06204
				12	5.15523	5.16141	0.25255
				13	0.18174	0.18345	0.02496
				14	-0.21186	0.21306	0.02257
				15	1.31403	1.31428	0.02554
				16	0.42394	0.42429	0.01715
				17	-0.09435	0.09504	0.01144
				18	0.10351	0.10519	0.01870

Pressure	250-900 psia
Mass Velocity	$2\text{-}3x10^6$ lbm/hr-ft^2
Quality	.4-.5
Points	9

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
28	54	0.06533	0.06812				
				1	-0.25755	0.29239	0.13842
				2	-0.41889	0.43346	0.11145
				3	-0.33358	0.35641	0.12550
				4	-0.46969	0.48078	0.10264
				5	1.71178	1.96103	0.95679
				6	-0.26060	0.29755	0.14360
				7	1.11943	1.21366	0.46888
				8	0.19380	0.29230	0.21882
				9	-0.47957	0.49091	0.10494
				10	0.70685	0.80246	0.37988
				11	0.12637	0.25104	0.21691
				12	2.86535	3.06126	1.07754
				13	-0.26931	0.30033	0.13294
				14	-0.10731	0.23131	0.20491
				15	0.59909	0.67735	0.31605
				16	-0.05087	0.18652	0.17945
				17	0.11333	0.42137	0.40585
				18	0.24318	0.44059	0.36741

Pressure	900-1500 psia
Mass Velocity	$0\text{-}1\text{x}10^6 \text{lbm/hr-ft}^2$
Quality	.4-.5
Points	54

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
29	76	0.05755	0.05762				
				1	-0.04604	0.16895	0.16255
				2	-0.25831	0.28769	0.12666
				3	-0.14639	0.20623	0.14526
				4	-0.32373	0.34383	0.11582
				5	2.42666	2.63145	1.01776
				6	-0.03861	0.18428	0.18019
				7	1.64028	1.70725	0.47347
				8	0.53817	0.59835	0.26152
				9	-0.32089	0.34372	0.12317
				10	0.75651	0.79454	0.24288
				11	0.45449	0.52336	0.25952
				12	4.17019	4.30725	1.07793
				13	-0.05585	0.16997	0.16053
				14	-0.14710	0.18372	0.11007
				15	1.03424	1.09211	0.35081
				16	0.21513	0.29867	0.20719
				17	-0.10292	0.15598	0.11720
				18	0.24011	0.31160	0.19860

Pressure	900-1500 psia
Mass Velocity	1-2x10^6 lbm/hr-ft^2
Quality	.4-.5
Points	77

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
30	57	0.05644	0.05655				
				1	0.26194	0.28515	0.11269
				2	-0.02165	0.08911	0.08644
				3	0.12716	0.16150	0.09956
				4	-0.10760	0.13369	0.07935
				5	3.96679	4.04417	0.78736
				6	0.27301	0.30417	0.13411
				7	2.45297	2.47380	0.32030
				8	1.03371	1.04926	0.18002
				9	-0.10494	0.14474	0.09969
				10	1.07127	1.08695	0.18397
				11	0.93513	0.95590	0.19819
				12	6.32196	6.36283	0.72003
				13	0.25073	0.27467	0.11215
				14	-0.21055	0.22615	0.08255
				15	1.68573	1.70313	0.24283
				16	0.60481	0.62129	0.14212
				17	0.00112	0.08691	0.08691
				18	0.34463	0.43180	0.26015

Pressure	900-1500 psia
Mass Velocity	2-3x10^{6}lbm/hr/ft^{2}
Quality	.4-.5
Points	57

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
31	53	0.05764	0.05768				
				1	-0.26734	0.28603	0.10168
				2	-0.47974	0.48432	0.06649
				3	-0.38258	0.39217	0.08617
				4	-0.51952	0.52288	0.05924
				5	1.66047	1.89634	0.91594
				6	-0.17230	0.20666	0.11410
				7	0.36695	0.41807	0.20032
				8	0.11094	0.17557	0.13608
				9	-0.42781	0.52941	0.31186
				10	0.58415	0.60295	0.14940
				11	0.31278	0.36563	0.18936
				12	2.41627	2.49231	0.61093
				13	-0.24168	0.26085	0.09815
				14	-0.28009	0.29156	0.08098
				15	0.44465	0.47409	0.16447
				16	-0.12974	0.17274	0.11405
				17	-0.05535	0.17832	0.16951
				18	0.09758	0.16622	0.13456

Pressure	250-900 psia
Mass Velocity	$0\text{-}1\times10^{6}$ lbm/hr-ft^{2}
Quality	.5-.7
Points	53

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
32	23	0.05784	0.05787				
				1	-0.08097	0.18326	0.16440
				2	-0.34111	0.36017	0.11561
				3	-0.22285	0.26074	0.13537
				4	-0.39090	0.40566	0.10842
				5	2.44679	2.62389	0.94764
				6	0.03675	0.22127	0.21819
				7	0.79105	0.85153	0.31521
				8	0.41719	0.48488	0.24710
				9	-0.36429	0.39988	0.16491
				10	0.74337	0.78561	0.25414
				11	0.64531	0.73976	0.36169
				12	3.64907	3.72128	0.72952
				13	-0.03939	0.17564	0.17116
				14	-0.23785	0.25609	0.09491
				15	0.85328	0.91572	0.33235
				16	0.10079	0.21529	0.19024
				17	-0.18989	0.21589	0.10272
				18	0.04016	0.13616	0.13011

Pressure	250-900 psia
Mass Velocity	1-2x10^6lbm/hr-ft^2
Quality	.5-.7
Points	23

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR     ERROF                  MN  ERROR    RMS ERROR    STD   DEV

   33         9  0.05690  0.05690
                                              1       0.16631      0.18278      0.07582
                                              2      -0.15597      0.16526      0.05461
                                              3      -0.00889      0.06302      0.06239
                                              4      -0.21942      0.22549      0.05199
                                              5       3.53609      3.57056      0.49497
                                              6       0.32434      0.34873      0.12812
                                              7       1.37605      1.38953      0.19309
                                              8       0.80366      0.81155      0.11285
                                              9      -0.23194      0.25133      0.09679
                                             10       1.01918      1.02474      0.10666
                                             11       1.07114      1.09222      0.21356
                                             12       5.36356      5.36810      0.22059
                                             13       0.20485      0.21760      0.07340
                                             14      -0.26490      0.26706      0.03387
                                             15       1.36804      1.37737      0.16007
                                             16       0.41132      0.42122      0.09077
                                             17      -0.10085      0.11327      0.05155
                                             18       0.10707      0.12086      0.05606
```

Pressure	250-900 psia
Mass Velocity	2-3x10^{6}lbm/hr-ft^2
Quality	.5-.7
Points	9

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
34	110	0.06074	0.06117				
				1	-0.25894	0.27807	0.10136
				2	-0.44681	0.45371	0.07883
				3	-0.36664	0.37712	0.08827
				4	-0.48271	0.48841	0.07442
				5	1.46402	1.70438	0.87266
				6	-0.10956	0.17634	0.13818
				7	0.76234	0.82872	0.32497
				8	0.13455	0.20189	0.15051
				9	-0.64442	0.64915	0.07821
				10	0.63691	0.68450	0.25076
				11	0.35965	0.42025	0.21740
				12	2.77885	2.89989	0.82907
				13	-0.27113	0.28801	0.09715
				14	-0.23316	0.26119	0.11772
				15	0.59741	0.64462	0.24215
				16	-0.08587	0.15528	0.12938
				17	-0.01352	0.24900	0.24864
				18	0.22293	0.32819	0.24085

Pressure	900-1500 psia
Mass Velocity	0-1x10^{6} lbm/hr-ft^{2}
Quality	.5-.7
Points	110

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
35	129	0.05752	0.05758				
				1	-0.01836	0.14527	0.14410
				2	-0.26937	0.29056	0.10894
				3	-0.16170	0.20394	0.12428
				4	-0.31744	0.33339	0.10190
				5	2.07703	2.29151	0.96797
				6	0.17591	0.25914	0.19029
				7	1.30091	1.36486	0.41291
				8	0.50908	0.55481	0.22059
				9	-0.51803	0.52867	0.10555
				10	0.74000	0.76627	0.19892
				11	0.79694	0.85174	0.30056
				12	4.17441	4.30122	1.03673
				13	-0.03158	0.14534	0.14186
				14	-0.19298	0.21653	0.09819
				15	1.09947	1.14470	0.31862
				16	0.20856	0.27586	0.18056
				17	-0.12335	0.16432	0.10857
				18	0.26762	0.32461	0.18371

Pressure	900-1500 psia
Mass Velocity	1-2x10^{6}lbm/hr-ft^{2}
Quality	.5-.7
Points	129

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR     ERROR                  MN  ERROR    RMS ERROR    STD   DEV

   36        69  0.05671   0.05678
                                            1        0.31403      0.34499      0.14285
                                            2       -0.02329      0.11021      0.10772
                                            3        0.12214      0.17499      0.12532
                                            4       -0.08825      0.13279      0.09923
                                            5        3.50681      3.63558      0.95903
                                            6        0.57027      0.60086      0.18928
                                            7        2.05603      2.09558      0.40526
                                            8        1.02456      1.04943      0.22715
                                            9       -0.34368      0.37048      0.13836
                                           10        1.06504      1.08528      0.20859
                                           11        1.39929      1.43177      0.30321
                                           12        6.56513      6.63733      0.97633
                                           13        0.29941      0.33313      0.14606
                                           14       -0.24874      0.25724      0.06558
                                           15        1.79931      1.82472      0.30347
                                           16        0.61736      0.64371      0.18229
                                           17        0.00877      0.09782      0.09743
                                           18        0.30108      0.33741      0.15230
```

Pressure	900-1500 psia
Mass Velocity	2-3x10^6lbm/hr-ft^2
Quality	.5-.7
Points	69

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR     ERROR                  MN   ERROR   RMS ERROR    STD    DEV

   37        48  0.06252   0.07177
                                              1     -0.25831      0.29266      0.13757
                                              2     -0.50495      0.51241      0.08716
                                              3     -0.45082      0.45850      0.08357
                                              4     -0.51965      0.52730      0.08949
                                              5      0.42456      0.69109      0.54530
                                              6      0.07282      0.27844      0.26874
                                              7     -0.04092      0.18466      0.18007
                                              8     -0.04682      0.13763      0.12942
                                              9     -0.83582      0.84601      0.13095
                                             10      0.39039      0.41996      0.15480
                                             11      1.24864      1.65630      1.08822
                                             12      1.34103      1.50530      0.68379
                                             13     -0.23192      0.26949      0.13724
                                             14     -0.39119      0.40331      0.09815
                                             15      0.46361      0.54419      0.28497
                                             16     -0.26278      0.28035      0.09770
                                             17     -0.27314      0.29675      0.11600
                                             18      0.11782      0.20399      0.16652
```

Pressure	250-900 psia
Mass Velocity	0-$1x10^6$ lbm/hr-ft^2
Quality	.7-1.
Points	48

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
38	17	0.05687	0.05690				
				1	-0.04924	0.16314	0.15553
				2	-0.36261	0.37614	0.09996
				3	-0.30325	0.32159	0.10707
				4	-0.37859	0.39166	0.10036
				5	0.72789	0.89868	0.52708
				6	0.41634	0.50646	0.28839
				7	0.17892	0.38133	0.33675
				8	0.20104	0.29824	0.22030
				9	-0.85217	0.85959	0.11274
				10	0.47998	0.54909	0.26667
				11	2.33112	3.13331	2.09368
				12	2.05628	2.32875	1.09307
				13	-0.01344	0.16367	0.16312
				14	-0.27768	0.29797	0.10808
				15	0.91294	0.96433	0.31061
				16	-0.07347	0.18963	0.17482
				17	-0.28985	0.30680	0.10057
				18	0.04354	0.16370	0.15780

Pressure	250-900 psia
Mass Velocity	1-2x10^{6}lbm/hr-ft^{2}
Quality	.7-1.
Points	17

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
39	94	0.05999	0.06018				
				1	-0.19657	0.24888	0.15265
				2	-0.43701	0.44925	0.10414
				3	-0.38928	0.40335	0.10558
				4	-0.45138	0.46341	0.10491
				5	0.59128	0.87496	0.64494
				6	0.23123	0.37221	0.29168
				7	0.22235	0.37160	0.29774
				8	0.03372	0.17487	0.17159
				9	-0.89334	0.89622	0.07177
				10	0.54730	0.60389	0.25523
				11	1.42774	1.79033	1.08019
				12	1.86440	2.07593	0.91296
				13	-0.21924	0.26139	0.14233
				14	-0.31761	0.33850	0.11708
				15	0.73297	0.81082	0.34668
				16	-0.16611	0.22309	0.14893
				17	-0.17929	0.24458	0.16635
				18	0.33430	0.40808	0.23403

Pressure	900-1500 psia
Mass Velocity	$0\text{-}1\text{x}10^6$ lbm/hr-ft^2
Quality	.7-1.
Points	94

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
40	62	0.05703	0.05711				
				1	0.03293	0.16265	0.15928
				2	-0.27431	0.29626	0.11191
				3	-0.20454	0.23871	0.12307
				4	-0.29569	0.31539	0.10971
				5	1.08365	1.36198	0.82505
				6	0.54850	0.61603	0.28043
				7	0.65864	0.75321	0.36541
				8	0.37737	0.44296	0.23195
				9	-0.83444	0.84024	0.09852
				10	0.61785	0.67409	0.26955
				11	1.84775	2.01869	0.81298
				12	3.11542	3.31837	1.14268
				13	0.01326	0.16135	0.16080
				14	-0.20485	0.23929	0.12366
				15	1.21281	1.26423	0.35687
				16	0.10908	0.22026	0.19135
				17	-0.17563	0.21918	0.13112
				18	0.26865	0.34051	0.20922

Pressure	900-1500 psia
Mass Velocity	1-2x10^{6} lbm/hr-ft^{2}
Quality	.7-1.
Points	63

DATA SET	POINTS	DATA MN ERROR	DATA RMS ERROR	CORRELATION	CORRELATION MN ERROR	CORRELATION RMS ERROR	CORRELATION STD DEV
41	27	0.05627	0.05631				
				1	0.23648	0.27206	0.13452
				2	-0.12901	0.16444	0.10197
				3	-0.03543	0.13298	0.12817
				4	-0.15823	0.18339	0.09271
				5	1.62910	1.78285	0.72430
				6	0.81193	0.82748	0.15970
				7	1.06499	1.15100	0.43657
				8	0.70561	0.75574	0.27066
				9	-0.76301	0.77263	0.12154
				10	0.75190	0.79776	0.26659
				11	2.17883	2.22005	0.42583
				12	4.60926	4.80170	1.34576
				13	0.21813	0.25443	0.13098
				14	-0.25160	0.25603	0.04740
				15	1.63059	1.65458	0.28072
				16	0.36679	0.42381	0.21231
				17	-0.09366	0.13878	0.10241
				18	0.18518	0.21441	0.10808

Pressure 900 1500 psia

Mass Velocity $2\text{-}3\times10^{6}$ lbm/hr-ft^2
Quality .7-1.
Points 27

Appendix F

CORRELATION EVALUATION FOR DIABATIC DATA SETS

The data sets in this appendix are the source sets identified in Table 5.1. The set numbers in this appendix coincide with those preceded by the letter D in that table. Table 5.1 gives the geometry and property ranges for each data set.

These results were obtained using the Thom void fraction correlation and the smooth tube singel-phase friction factor to reduce the data.

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION   CORRELATION   CORRELATION
                   ERROR     ERROR                  MN   ERROR    RMS ERROR     STD    DEV

    1        15  0.13263   0.14792
                                                1    -0.54512       0.59756       0.24478
                                                2    -0.63515       0.65702       0.16812
                                                3    -0.58952       0.62199       0.19834
                                                4    -0.66752       0.68640       0.15987
                                                5    -0.13379       0.73716       0.72398
                                                6    -0.48064       0.55904       0.30462
                                                7     0.26020       0.56649       0.50320
                                                8    -0.25492       0.43795       0.35612
                                                9    -0.66677       0.67422       0.09993
                                               10    -0.05512       0.42823       0.42472
                                               11    -0.31611       0.51566       0.52947
                                               12     0.87546       1.65958       1.40938
                                               13    -0.55126       0.60100       0.23941
                                               14    -0.49661       0.53162       0.18975
                                               15    -0.05666       0.54373       0.54077
                                               16    -0.42026       0.51170       0.29192
                                               17    -0.47257       0.51434       0.20303
                                               18    -0.30177       0.42488       0.29909
```

```
DATA SET  POINTS  DATA MN  DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR    ERROR                  MN   ERROR   RMS  ERROR   STD    DEV

     2      121  0.07348  0.07691
                                               1   -0.11148      0.35157      0.33343
                                               2   -0.29421      0.38753      0.25224
                                               3   -0.20429      0.35118      0.28565
                                               4   -0.35676      0.42742      0.23539
                                               5    0.05437      1.54554      1.28793
                                               6    0.02865      0.45254      0.45163
                                               7    1.45072      1.76342      1.00253
                                               8    0.43229      0.66596      0.50658
                                               9   -0.35906      0.44643      0.26528
                                              10    0.60117      0.73812      0.42823
                                              11    0.39471      0.89621      0.80461
                                              12    3.15840      3.81176      2.13401
                                              13   -0.12217      0.34455      0.32217
                                              14   -0.23959      0.27797      0.14077
                                              15    0.86313      1.13634      0.73911
                                              16    0.12741      0.43253      0.41334
                                              17   -0.17118      0.26626      0.20394
                                              18    0.05518      0.27235      0.26670
```

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR     ERROR                  MN   ERROR   RMS  ERROR   STD    DEV

    3        70  0.06439   0.06470
                                                1     0.02678      0.34553      0.34450
                                                2    -0.20740      0.32978      0.25641
                                                3    -0.10057      0.31223      0.29559
                                                4    -0.27160      0.36071      0.23738
                                                5     1.47772      2.06412      1.44116
                                                6     0.19008      0.48743      0.44884
                                                7     1.64341      1.89870      0.95092
                                                8     0.62161      0.82051      0.53558
                                                9    -0.35501      0.47495      0.31551
                                               10     0.83819      0.94120      0.42813
                                               11     0.76915      1.20019      0.92134
                                               12     3.98915      4.57857      2.24722
                                               13     0.01197      0.33880      0.33859
                                               14    -0.15555      0.19101      0.11085
                                               15     1.17187      1.38556      0.73926
                                               16     0.27997      0.50969      0.42591
                                               17    -0.06428      0.18516      0.17355
                                               18     0.27050      0.35733      0.23349
```

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR     ERROR                 MN   ERROR   RMS ERROR    STD    DEV

    4       159   0.07493   0.07651
                                            1        0.10688      0.33843      0.32111
                                            2       -0.11689      0.25140      0.22257
                                            3       -0.01348      0.25963      0.25928
                                            4       -0.19423      0.28645      0.21054
                                            5        1.18663      1.90890      1.49526
                                            6        0.33288      0.59462      0.49272
                                            7        1.97147      2.18753      0.94795
                                            8        0.77731      0.90965      0.47249
                                            9       -0.21027      0.40109      0.34156
                                           10        0.86604      0.96273      0.42051
                                           11        0.81546      1.34842      1.07390
                                           12        4.06665      4.67306      2.30213
                                           13        0.09556      0.32656      0.31226
                                           14       -0.15497      0.20151      0.12880
                                           15        1.29792      1.49032      0.73243
                                           16        0.38762      0.54763      0.38684
                                           17       -0.06032      0.20066      0.19138
                                           18        0.17723      0.31613      0.26177
```

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                  ERROR     ERROR                  MN   ERROR   RMS ERROR    STD    DEV

    5       270  0.06842   0.06970
                                             1      -0.09927      0.28917      0.27160
                                             2      -0.27173      0.33945      0.20345
                                             3      -0.18198      0.29674      0.23438
                                             4      -0.34034      0.38787      0.18605
                                             5       0.71643      1.37645      1.17531
                                             6       0.04836      0.35661      0.35331
                                             7       1.57651      1.75964      0.78164
                                             8       0.49001      0.64736      0.42305
                                             9      -0.30689      0.40538      0.26485
                                            10       0.66877      0.75120      0.34213
                                            11       0.32186      0.69207      0.61267
                                            12       3.11740      3.66696      1.93091
                                            13      -0.11112      0.29025      0.26814
                                            14      -0.19840      0.22787      0.11208
                                            15       0.87320      1.05699      0.59561
                                            16       0.15883      0.37605      0.34086
                                            17      -0.14165      0.20438      0.14734
                                            18       0.13368      0.22986      0.18699
```

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR     ERROR                 MN   ERROR   RMS  ERROR   STD    DEV

     6        71  0.08011   0.08246
                                                1    -0.06683      0.38878      0.38298
                                                2    -0.26376      0.38642      0.28241
                                                3    -0.16719      0.36717      0.32690
                                                4    -0.32847      0.42004      0.26179
                                                5     1.07495      1.94347      1.61913
                                                6     0.08267      0.47679      0.46957
                                                7     1.54089      1.83515      0.99671
                                                8     0.50987      0.77910      0.58909
                                                9    -0.34781      0.45857      0.29886
                                               10     0.68007      0.85641      0.52053
                                               11     0.47119      0.94685      0.82128
                                               12     3.50197      4.27846      2.45793
                                               13    -0.07865      0.38590      0.37780
                                               14    -0.22834      0.27146      0.14680
                                               15     0.96007      1.26381      0.82955
                                               16     0.18575      0.50773      0.47253
                                               17    -0.14992      0.27124      0.22605
                                               18     0.13679      0.33253      0.30309
```

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR     ERROR                  MN   ERROR   RMS  ERROR   STD    DEV

    7       309  0.08798   0.08955
                                                1    -0.12381      0.45719      0.44011
                                                2    -0.32141      0.45660      0.32431
                                                3    -0.22185      0.43325      0.37214
                                                4    -0.38286      0.48854      0.30347
                                                5     1.19973      1.97675      1.57104
                                                6    -0.04559      0.57048      0.56865
                                                7     1.26164      1.67350      1.09949
                                                8     0.40834      0.78306      0.66817
                                                9    -0.33338      0.46304      0.32135
                                               10     0.62763      0.87928      0.61581
                                               11     0.37061      0.98302      0.91048
                                               12     3.23603      4.14988      2.59799
                                               13    -0.11940      0.45237      0.43633
                                               14    -0.24926      0.32148      0.20303
                                               15     0.83041      1.25645      0.94291
                                               16     0.10473      0.54454      0.53437
                                               17    -0.17354      0.32166      0.27083
                                               18    -0.00103      0.33220      0.33220
```

```
DATA SET  POINTS  DATA MN  DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR    ERROR                  MN   ERROR   RMS ERROR    STD    DEV

    8       143  0.07056  0.07148
                                              1     0.22493     0.52210      0.47117
                                              2    -0.05510     0.33953      0.33503
                                              3     0.08092     0.39134      0.38288
                                              4    -0.13443     0.34581      0.31861
                                              5     2.53163     3.15807      1.88792
                                              6     0.36092     0.73239      0.63728
                                              7     2.19212     2.39596      0.96707
                                              8     0.95772     1.17758      0.68516
                                              9    -0.19066     0.34606      0.28880
                                             10     1.11397     1.26132      0.59160
                                             11     0.98784     1.47730      1.09845
                                             12     5.46219     6.17904      2.88878
                                             13     0.21341     0.51305      0.46656
                                             14    -0.09830     0.19780      0.17164
                                             15     1.58972     1.88308      1.00934
                                             16     0.54519     0.77472      0.55042
                                             17     0.05096     0.27478      0.27002
                                             18     0.37282     0.49140      0.32013
```

```
DATA SET  POINTS  DATA MN  DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR    ERROR                  MN   ERROR   RMS ERROR    STD    DEV

    9        12  0.10207  0.10464
                                               1   -0.54832      0.54920      0.03110
                                               2   -0.58903      0.59001      0.03404
                                               3   -0.56006      0.56100      0.03249
                                               4   -0.63226      0.63306      0.03181
                                               5   -0.57193      0.57308      0.03633
                                               6   -0.48717      0.48799      0.02835
                                               7    0.46139      0.47095      0.09441
                                               8   -0.19476      0.20345      0.05884
                                               9   -0.53201      0.53321      0.03567
                                              10   -0.10955      0.11969      0.04821
                                              11   -0.51912      0.51980      0.02654
                                              12    0.36870      0.38536      0.11209
                                              13   -0.55343      0.55428      0.03072
                                              14   -0.51686      0.51836      0.03933
                                              15   -0.14336      0.15114      0.04785
                                              16   -0.40828      0.40995      0.03688
                                              17   -0.52491      0.52734      0.05056
                                              18   -0.25155      0.25331      0.02977
```

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR     ERROR                  MN   ERROR   RMS  ERROR   STD    DEV

   10         5  1.45916   1.45955
                                                1     -0.53102      0.55249      0.15253
                                                2     -0.55675      0.57335      0.13698
                                                3     -0.53766      0.55771      0.14822
                                                4     -0.59366      0.60555      0.11941
                                                5     -0.53027      0.54974      0.14500
                                                6     -0.51324      0.54033      0.16893
                                                7      0.37316      0.67410      0.56139
                                                8     -0.18764      0.34803      0.29311
                                                9     -0.51422      0.53879      0.16083
                                               10     -0.02338      0.35470      0.35393
                                               11     -0.51298      0.53729      0.15977
                                               12      0.00799      0.67032      0.67027
                                               13     -0.53983      0.56056      0.15103
                                               14     -0.43891      0.48271      0.20091
                                               15     -0.19630      0.37280      0.31694
                                               16     -0.41874      0.46870      0.21056
                                               17     -0.43330      0.47378      0.19162
                                               18     -0.21475      0.31926      0.23623
```

```
DATA SET  POINTS  DATA MN   DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR     ERROR                  MN   ERROR   RMS  ERROR   STD    DEV

   11        31  0.74828   1.14923
                                            1       -0.49410     0.68698      0.47729
                                            2       -0.52210     0.68747      0.44725
                                            3       -0.50163     0.68660      0.46881
                                            4       -0.56005     0.69516      0.41180
                                            5       -0.47846     0.67091      0.47032
                                            6       -0.47236     0.70942      0.52929
                                            7        0.44301     1.47207      1.40383
                                            8       -0.13888     0.81938      0.80752
                                            9       -0.47854     0.68646      0.49216
                                           10        0.10059     1.12903      1.12454
                                           11       -0.47090     0.68930      0.50338
                                           12       -0.09254     1.14620      1.14246
                                           13       -0.50335     0.68907      0.47059
                                           14       -0.36169     0.76742      0.67684
                                           15       -0.14432     0.84655      0.83415
                                           16       -0.37779     0.70603      0.59645
                                           17       -0.26488     0.88286      0.84219
                                           18       -0.02892     0.92496      0.92450
```

```
DATA SET  POINTS  DATA MN  DATA RMS  CORRELATION  CORRELATION  CORRELATION  CORRELATION
                   ERROR    ERROR                  MN   ERROR   RMS  ERROR    STD    DEV

   12        25  1.42165  1.42172
                                               1     -0.14790      0.94718      0.93556
                                               2     -0.27883      0.87246      0.82670
                                               3     -0.20322      0.92187      0.89919
                                               4     -0.34470      0.82112      0.74527
                                               5      0.38424      0.83934      0.74622
                                               6      0.00091      1.17838      1.17837
                                               7      1.80581      3.75628      3.29373
                                               8      0.40469      1.63313      1.58219
                                               9     -0.31421      0.92506      0.87006
                                              10      1.35288      2.96117      2.63405
                                              11      0.12929      1.09875      1.09112
                                              12      1.91158      3.20944      2.57805
                                              13     -0.17400      0.92131      0.90473
                                              14      0.34647      1.65977      1.62320
                                              15      0.78838      2.06306      1.90648
                                              16      0.11812      1.25320      1.24762
                                              17      1.10886      2.68889      2.44960
                                              18      0.57057      1.85740      1.76759
```

Appendix G

VOID FRACTION REFERENCES

For the purposes of future studies similar to this one, for void fraction models and correlations, the references that are applicable are : 1, 2, 3, 4, 5, 6, 9, 11, 12, 13, 15, 25, 27, 30, 33. Additional references dealing with void fraction models and data include:

B. Panella, "Measurement of Void Fraction with an Impedance Void Meter," AE-RL-1258, Oct. 1970.

J. F. Marchaterre and B. F. Hoglund, "Correlation for Two-Phase Flow," Nucleonics, Vol. 20, No. 8, Aug. 1962.

S. Ziu Rouhani, "Calculation of Steam Volume Fraction in Subcooled Boiling," ASME paper 67-HT-31.

S. M. Zivi, "Estimation of Steady State Steam Void-Fraction by Means of the Principal of Minimum Entropy Production," ASME paper 63-HT-16.

P. Griffith, "The Prediction of Low-Quality Boiling Voids," ASME papter 63-HT-20.

N. Zuber and J. A. Findlay, "Average Volumetric Concentration in Two-Phase Flow Systems," Journal of Heat Transfer, Nov. 1965.

S. Levy, "Forced Convection Subcooled Boiling-Prediction of Vapor Volumetric Fraction," Int. J. Heat Mass Transfer, Vol. 10, 1967.

J. F. Marchaterre et all, "Natural and Forced-Circulation Boiling Studies," ANL-5735, May, 1960.

C. J. Baroczy, "Correlation of Liquid Fraction in Two-Phase Flow with Application to Liquid Metals," Chemical Engineering Symposium Series, 1963.

E. E. Polomik, "Phase Velocities in Boiling Flow Systems by Total Energy and by Diffusion," ASME paper 65-HT-34.

G. W. Maurer, "A Method of Predicting Steady-State Boiling Vapor Fractions in Reactor Coolant Channels," WAPD-TH-19, June 1960.

H. Christensen, "Power to Void Transfer Functions," ANL-6385, July 1961.

"Metering of Two Phase-Mixtures: Report of a Meeting at NEL 6th January, 1965," NEL-217.

N. Zuber et al, "Steady State and Transient Void Fraction in Two-Phase Flow Systems. Final Report for the Program of Two-Phase Flow Investiagtion," GEAP-5417, Jan. 1967.

D. Nylund et al, "Measurements of Hydrodymanic Characteristics, Instability Thresholds, and Burnout Limits for 6-Rod Clusters in Natural and Forced Circulation," FRIGG-1, June 1967.

D. Nylund et al, "Hydrodynamic and Heat Transfer Measurements on a Full-Scale Simulated 36-Rod Marviken Fuel Element with Uniform Heat Flux Distribution," FRIGG-2, 1967.

Kroeger, R. G. and N. Zuber, "A Program of Two-Phase Flow Investigation," GEAP-5275, Oct. 1966.

S. Levy "Forced Convection Boiling: Prediction of Vapor Volumetric Fraction," GEAP-5157, Apr. 1966.

R. T. Lahey et al, "Analysis of Transient Critical Heat Flux," GEAP-13249, Feb. 1972.