US AEC report COO- 2152-15

Two Phase Pressure Drop
Across Abrupt Area Changes

by A. Husain
J. Weisman

University of Cincinnati
Cincinnati, Ohio 45221

January 1975

Work supported by U.S. Atomic Energy Commission Contract
AT-11-1-2152

—NOTICE—

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

22

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Contents

<u>1.0 Introduction</u>	
1.1 Background	1
1.2 Objectives of Program	1
<u>2.0 Testing and Analysis Program</u>	
2.1 Overall Approach	1
2.2 Boiling Free Loop Description	2
2.3 Test Program	4
2.4 Experimental Procedure	6
2.5 Experimental Results	7
<u>3.0 Analysis of Abrupt Area Change Pressure Losses</u>	
3.1 Analysis of Abrupt Expansion Data	11
3.2 Analysis of Contraction Data	27
3.3 Analysis of Contraction-Expansion Combinations	36
<u>4.0 Conclusions and Recommendations</u>	41
<u>References</u>	44
<u>Appendix</u>	
A - Void Meter Description and Calibration	46
B - Experimental Data Tabulation and Data Reduction Procedures	56
C - Error Analysis	76
D - Comparison of Measured Data With Analytical Predictions	81

1.0 Introduction

1.1 Background

The prediction of two-phase (vapor-liquid) pressure drops across abrupt area changes has been the subject of several investigations⁽¹⁻⁶⁾. Nevertheless at the outset of the present study there still appeared to be unresolved questions. The reviews of both Collier⁽⁷⁾ and Lahey⁽⁸⁾ state that a slip-flow model describes expansion pressure drop but that the homogeneous model describes pressure drop across contractions. Fitzsimmons⁽⁵⁾ however, found both his expansion and contraction data were correlated by the homogeneous model. Janssen⁽³⁾ found that his data for expansion-contraction combinations were best described by a model which assumed slip flow upstream and downstream but mixing at the vena contracta. No single coherent model appeared to be fully capable of explaining all of the available data.

1.2 Objectives of Program

This research was undertaken to develop a coherent view of two-phase pressure drop across abrupt area changes during steady flow. Specifically the objectives of this program were to:

- a) establish an additional data base of observations of two-phase pressure drop across abrupt area changes.
- b) determine whether a single model based one-dimensional momentum theory can correlate the data obtained in the present investigation as well as that in the literature.

2.0 Testing and Analysis Program

2.1 Overall Approach

Examination of the data available in the literature indicated that most of the pressure drop measurements across abrupt area changes were made with the steam-water system. To assure the generality of the correlating approaches developed, it was decided to conduct the test program with a non-water system.

The Freon-Freon vapor system was selected for this purpose. Specifically, Freon 113 (molecular wt = 187.39, boiling point at atm. pressure = 117.5°F), was the fluid chosen. The low heat of vaporization (59.5 Btu/lb at 2 atm) of Freon 113 meant that heat addition requirements were low. In addition, the high molecular weight of Freon 113 meant that Freon vapor densities would be the same order of magnitude as the steam in a reactor system.

An available loop, capable of producing a mixture of Freon liquid and vapor, was modified for these tests. The first part of the experimental program consisted of a series of observations of the transition from homogeneous to non-homogeneous flow. These observations, and the correlation derived for predicting this transition, will be presented in a subsequent report.

The bulk of the experimental observations were devoted to abrupt area change pressure drops. The data obtained and the available information from the literature were tested against several predictions based upon a one-dimensional momentum balance.

2.2 Boiling Freon Loop Description

The experimental observations were made using the University of Cincinnati's Boiling Freon Loop. This loop is shown schematically in Fig. 1. The main loop piping is $1\frac{1}{2}$ " schedule 40 carbon steel. The liquid Freon is circulated by a 30 gpm centrifugal pump provided with a specially balanced seal to prevent Freon leakage. On leaving the pump, liquid flows to a specially bored pipe section containing an orifice for flow measurement.

Freon vapor is generated in two vertical sections by means of electric immersion heaters (30 kw capacity). The two phase mixture then flows through the test section which generally contained some glass piping. A flexible hose at the end of the test section accommodates differential expansion.

Fig. 1 Boiling Freon Loop for Steady State Pressure Drop and Flow Pattern Observations

The two-phase mixture leaving the test section proceeds to a water cooled condenser. The condensate returns to the pump inlet and is re-circulated.

Pressure on the system is maintained by means of a large bladder type accumulator. The rubber diaphragm in the accumulator prevents contact between the Freon and the nitrogen used to maintain gas overpressure.

Test section pressure drops are measured by a multi range (0 - 10 to 0 - 100 in water) bellows type differential pressure cell (Honeywell Model 29). A manifold arrangement allows all pressure drops to be read on the single cell. Cooling jackets supplied with tap water assure that the lines to the differential pressure cell contain only liquid. Cooling jackets are also provided on the lines leading to the differential pressure cell measuring pressure drop across the orifice in the main liquid flow.

Although the heat input to the loop is measured by means of ammeters and voltmeters on the electrical lines to the heaters, these measurements are not used to calculate flow quality. Previous experience with Freon systems⁽⁹⁾ has indicated that dissolved air can lead to highly erroneous void estimations when void and quality are computed via heat balances. Further, because of Freon's low heat of vaporization, a 1 °F error in liquid temperature measurement can lead to a void fraction error of up to 0.14.

2.3 Test Program

Abrupt area change test sections having area ratios (σ 's) of 0.25 and 0.56 were examined. The dimensions of the test sections examined are shown in Fig. 2. The first test section ($\sigma = .25$) was constructed of specially bored steel pipe. The second test section ($\sigma = 0.56$) was constructed of glass pipe and visual and photographic observations were made along with the pressure drop measurements.

Fig. 2. Abrupt Area Change Test Sections

The test conditions covered mass velocities from about 1×10^6 lbs/hr ft² to about 2.5×10^6 lbs/hr ft² (based on small size pipe). Pressures were varied from approximately 30 to 75 psia.

During checkout tests of the apparatus, pressure changes were measured across the contraction and expansion individually. Because of the low pressure change across the expansion (frictional Δp counter-balances much of Bernoulli pressure rise) it was difficult to obtain consistent pressure change measurements across the expansion. Further, the literature contained only limited measurements of the pressure drop across expansion-contraction combinations. It was therefore decided to measure the pressure drops across the contraction and the contraction-expansion combination. Thus, in test section #1, pressure drop data were taken across the entire section and between the central tap and downstream tap. In test section #2, data were obtained across the entire section and between the upstream tap and central tap.

For the first test section ($\sigma = 0.25$), void fractions were measured by a single capacitance type voidmeter (see Appendix A for description) placed approximately 3 feet upstream of the test section. For the second test section ($\sigma = .56$), high velocities and pressure drops were encountered. The possibility of measureable Freon vaporization in the test section therefore existed. To examine this question, a second capacitance type void sensor was installed approximately $1\frac{1}{2}$ ft downstream of the test section. Void changes across the test section could therefore be determined.

2.4 Experimental Procedure

At the beginning of each run, the freon in the loop was fully liquid and at room temperature. Before the pump was started, the differential pressure cell was checked to ascertain that the reading was zero. Flow

was then initiated and the electrical heaters set at the desired level for heat up. During the heating period, the system pressure was slowly increased to the desired operating level thus maintaining all liquid in the system. The effect of the temperature increase on the output of the void sensors was recorded and plotted. Single phase pressure drop data was also checked to be certain that the system was operating properly.

The pressure level was maintained constant during any given run by setting the gas-pressure regulators. Void fractions were increased by a stepwise increase in the electrical heat input. Flow was maintained constant during the run by adjusting the throttle and pump bypass valves. Coolant flow to the condenser was adjusted to maintain the temperature of the fluid entering the pump at a level low enough to prevent cavitation.

The onset of two-phase operation was observed through a straight pipe glass viewing section with test section #1 and through the glass area change section itself in that section #2. No pressure drop data were recorded until the system had been fully stable for about 15-20 minutes. After the desired data was obtained, the heat input was increased and the process repeated. Flow and pressure were maintained constant until the entire void fraction range of interest was examined.

2.5 Experimental Results

The void fraction data obtained from the runs where void sensors were present upstream and downstream of the test section were examined. It was found that at the lower mass velocities (see Fig. 3) the void fractions measured upstream and downstream of the test section agreed well. When the mass velocity in the smaller pipe was significantly in excess of 2×10^6 lbs/hr ft², the void fraction downstream was significantly greater than

Fig. 3. Comparison of Void Fraction Measurements Upstream and Downstream of Abrupt Area Change
(Working Fluid - Freon 113)

Legend

G (large pipe)	25 psig	40 psig	60 psig	G (small pipe)
$1.12 \times 10^6 \text{ lb/hr ft}^2$	○	▽	□	$2 \times 10^6 \text{ lb/hr ft}^2$
$1.38 \times 10^6 \text{ " "}$	●	▼	■	$2.47 \times 10^6 \text{ lb/hr ft}^2$
$1.59 \times 10^6 \text{ " "}$		▽		$2.84 \times 10^6 \text{ lb/hr ft}^2$

that upstream. The observation of significant vaporization coincides approximately with the onset of homogeneous flow (as determined by both U.C. observations and analysis of literature data). In slug flow or stratified flow, contact between the phases is limited and heat and mass transfer between the phases may be expected to be low. Under homogeneous flow conditions, good contact between the phases may be expected and significant vaporization seen. It should be noted that vaporization effects will be far more significant in a Freon system than in steam-water systems because of the low heat of vaporization of Freon.

In analyzing the contraction data, the highest mass velocity data were excluded. Although the total vaporization across both expansion and contraction was known, that portion which had occurred during the contraction process was not known. Hence, the appropriate correction term is not available. The effect of the Freon vaporization in the high mass velocity data for the expansion-contraction combination was accounted for by subtracting an acceleration pressure drop term from the measured loss. The acceleration pressure drop was based on an overall balance between inlet and outlet conditions and was computed in the usual manner⁽¹⁰⁾.

The measured pressure drops included both the pressure drop due to the area change as well as the pipe friction losses between the pressure taps. The frictional pressure drop in the straight pipe was subtracted from the observed total in order to get that due to the area change. Baroczy's⁽¹¹⁾ correlation was used for estimation of the two-phase friction multiplier for all cases except conditions where stratified flow occurred (occurrence of separated flow based on visual observations in straight glass pipe test section). The data of McMillan⁽¹²⁾ show that under stratified flow conditions the Baroczy correlation overpredicts the frictional losses. In the range of interest in the current

experiments it was concluded from McMillan's data that the two phase frictional drop multiplier, ϕ^2 , in separated flow could be represented approximately as

$$\phi_1^2 = 0.7 \phi_{\text{homog}}^2 \quad (1)$$

where ϕ_{homog}^2 = two phase multiplier assuming homogeneous flow.

It was also concluded that in the second test section ($\sigma = 0.56$) a further correction to the measured pressure loss across the contraction-expansion combination was required. Examination of Mendler's⁽¹⁾ expansion data indicated that the pressure tap placed after the expansion was somewhat too close to gain full pressure recovery. Mendler's data on Δp vs length (Mendler's large size pipe was 1 inch in diameter as was the large size pipe for the second test section) was used to determine the fraction of the pressure drop which remained unrecovered at the tap location used in these tests.

The experimental data obtained in this study are tabulated in Appendix B. The corrections required to reduce the data are also tabulated. Sample calculations showing how they were obtained are provided

The reduced data are plotted in the form of the ratio ($\Delta P_{\text{TP}}/\Delta P_{\text{SP}}$) of two phase to single phase pressure drop vs void fraction, (α) in Figs. 4-11. Mass velocities (G) shown are based on the small size pipe for the given test section. The data exhibit the usual scatter seen in two phase pressure drop measurements. An error analysis (See Appendix C for details of error analysis) indicate that the maximum error in the pressure drop

ratio ranges from approximately 16% at high flow and α 's to about 50% at low flow and low α 's. Appropriate error bars are through the data points of Figs. 4 - 11.

The curves shown in Figs. 4 - 11 represent various pressure drop models developed on the basis of a one dimensional momentum balance (Models described in detail in Section 3 of this report). In all cases the lowest of these curves represents a slip flow model in which α is the void fraction expected in flow through straight pipe of the same diameter. The data generally tend to be above the slip model curves. A slight pressure trend might seem to be indicated by the contraction data since the 30 psi data are closest to the slip model line. However, the expansion-contraction data do not bear out this trend. Here, the 30 psi data at high voids are clearly well above the slip model curve.

3.0 Analysis of Abrupt Area Change Pressure Losses

3.1 Analysis of Abrupt Expansion Data

Although direct measurement of expansion pressure changes were not made in the present tests, an understanding of this behavior will be useful in the examination of the present data. Pressure changes across expansions during two-phase flow have been measured by Fitzsimmons⁽⁵⁾, Mendler⁽¹⁾, Ferrell and McGee⁽²⁾, and Janssen and Kervinen⁽⁶⁾. In each of these investigations the steam-water system was examined.*

*The analysis was restricted to one component systems and hence, the earlier air-water data by B.L. Richardson [("Some Problems in Horizontal Two-Phase Two-Component Flow" - ANL 5949 (1958))] were not included.

Fig. 4. Ratio of Two-Phase to Single-Phase Pressure Drop Across a Contraction (System Pressure=75 PSIA)

Fig. 5. Ratio of Two-Phase to Single-Phase Pressure Drop across a Contraction. (System Pressure = 65 PSIA)

Fig. 6. Ratio of Two-Phase to Single-Phase Pressure Drop Across a Contraction. (System Pressure = 40 PSIA)

Fig. 7. Ratio of Two-Phase to Single-Phase Pressure Drop Across a Contraction (System Pressure = 30 PSIA)

Fig. 8. Ratio of Two-Phase to Single Phase Pressure Drop Across a
 Long-Expansion-Contraction Geometry (Pressure = 75 psia)
 Freon-Freon Vapor System

Fig. 9. Ratio of Two-Phase to Single-Phase Pressure Drop Across a Long
 Expansion-Contraction Geometry (Pressure = 55 psia)
 Freon-Freon Vapor System

Fig. 10. Ratio of Two-Phase to Single-Phase Pressure Loss Across a Long Expansion-Contraction Geometry ($P = 40$ psia)
 Freon-Freon Vapor System

Fig. 11. Ratio of Two-Phase to Single-Phase Pressure Drop Across a Long Expansion-Contraction Geometry (Pressure = 30 psia)
 Freon-Freon Vapor System

In the analysis of abrupt expansion data, it is generally assumed that one dimensional momentum theory may be applied. The momentum balance must be made across planes which are sufficiently distant from the area change so that a one dimensional flow pattern may be assumed⁽¹³⁾. Using Fig. 12, the momentum balance is made by considering the momentum flux across planes 1 and 2. In single phase flow, the inference is made, confirmed by observation, that the pressure is approximately uniform across the pipe at the sudden enlargement. Further, the upstream pressure, p , is acting on the pipe wall at position "0". For a single phase fluid of density, ρ , one obtains, for conditions where pipe friction is negligible,

$$p_2 - p_1 = \frac{G_T^2}{\rho g_c} \sigma^2 \left[\frac{1}{\sigma} - 1 \right] \quad (2)$$

The validity of this equation for single phase flow is well documented.

Using the same set of assumptions for two phase flow plus the assumption that the liquid and vapor velocities can be represented by single values at a given cross section, Lottes⁽¹⁴⁾ reports that Romie obtained

$$\Delta p_\epsilon = \frac{G_T^2 \sigma^2}{\rho_1 g_c} \left[\frac{\rho_1}{\rho_g} x^2 \left(\frac{1}{\alpha_1 \sigma} - \frac{1}{\alpha_2} \right) + [(1-x)^2 \left(\frac{1}{\sigma(1-\alpha_1)} - \frac{1}{(1-\alpha_2)} \right)] \right] \quad (3)$$

where

Δp_ϵ = pressure rise between locations 1 and 2 assuming pipe friction is negligible

ρ_g, ρ_1 = gas and liquid densities, respectively

G_T = total mass velocity based on area of smaller pipe (lbs/hr ft²)

x = quality (lbs vapor/lb total fluid flowing)

σ = area ratio

α_1, α_2 = void fraction at locations 1 and 2 (see Fig. 12)

Fig. 12. Abrupt Expansion Schematic

Fig. 15. Abrupt Contraction Schematic

Janssen⁽³⁾ has made a similar analysis and arrived at the same conclusion.

There has been some questioning of the assumption that the pressure, p_1 , is acting at position "0". However, in view of the fact that the same assumption has worked well for the analysis of single phase flow, the use of another assumption does not appear to be justified at this time.

Use of Equation (3) requires a knowledge of the values of α_1 and α_2 . Since the values of α_1 and α_2 were generally not measured in the steam-water experiments, they usually must be inferred from the measured quality. One possible assumption is that the flow may be considered to be homogeneous upstream and downstream of the test section. Under conditions where the quality remains constant across the test section (essentially true for each of the sets of test data being considered)

$$\alpha_1 = \alpha_2 = \frac{x}{(x + (1-x)(\rho_g/\rho_l))} \quad (4)$$

The results obtained with this assumption are shown in Fig. 13. It is seen that the model tends to predict pressure changes above those observed.

Since under most of the test conditions homogeneous flow is not expected, it is more reasonable to assume that slip flow exists upstream and downstream of the expansion. The values of α_1 and α_2 may then be estimated (if it is assumed that they correspond to the values for fully developed flow in a straight pipe) using an appropriate relationship between x and α . The correlation of Hughmark⁽¹⁵⁾ was chosen for the purpose since it includes a velocity effect which leads to slips approaching one at high fluid velocities. This is in accord with the visual observation that the flow tends towards homogeneous flow as velocity is increased.

Fig. 13. Comparison of Pressure Rise Measured Across an Expansion With Pressure Rise Predicted by Using all Homogeneous Model. (Model E).

Fig. 14. Comparison of Pressure Rise Measured Across an Expansion With Pressure Rise Predicted by Using All Slip Model, (Model F).

Fig. 14 compares the experimental results and the predictions obtained assuming slip flow. Comparison of Figs. 13 and 14 shows that the slip flow model (Fig. 14) provides a better representation of the data. With the homogeneous model approximately 95% of the data points lie between the ratios $\Delta P_m / \Delta P_p = 2.7$ and $\Delta P_p / \Delta P_m = 2.7$ (ΔP_p = predicted ΔP , ΔP_m = measured ΔP). With use of the slip model, approximately 95% of the data points lie between the ratios $\Delta P_m / \Delta P_p = 2.0$ and $\Delta P_p / \Delta P_m = 2.0$. The comparison may be further quantified by a statistical analysis of the data. Following Dukler et al.⁽¹⁶⁾, we define a fractional deviation, d_i , such that

$$d_i = (P_i - M_i) / M_i \quad (5)$$

where P_i = predicted value for i^{th} data point

M_i = measured value of i^{th} data point

The average fractional deviation, $\bar{d}$, is then

$$\bar{d} = \frac{\sum_{i=1}^n d_i}{n} \quad (6)$$

An estimate, $s(d)$ of the standard deviation of d is then given by

$$s(d) = \sqrt{\frac{\sum_{i=1}^n d_i^2}{n} - \bar{d}^2} \quad (7)$$

where n = no. of data points.

If the population were normal, we would expect to see approximately 95% of the data included within 2σ of the mean. However, as noted by Dukler et al.⁽³⁴⁾, d_i , by definition can range only from -1 to ∞ . Because of the fixed lower bound d_i , cannot be normally distributed. The value of s is thus not completely descriptive of the data spread. Nevertheless, the standard

deviation does provide an indication of data dispersion and it will therefore be used here.

Statistical analysis of all of the expansion data shows the following:

Table 1 - Statistical Evaluation of Abrupt Expansion Data

	Homogeneous Model	Slip Model
$\bar{d}$, average fractional deviation	0.417	-.040
$s(d)$, standard deviation of d	0.771	.495

Both the average fractional deviation and the standard deviation are, as expected, substantially lower for the slip model than for the homogeneous model. The very low value of $\bar{d}$ for the slip model indicates that this model provides a good fit of the data. The relatively high value of $s(d)$ is in part a reflection of the difficulty in obtaining accurate values for ΔP_E in view of the generally low values of measured pressure change (friction counterbalances the pressure rise). In addition, further scatter has probably been introduced by the necessity of estimating α from quality. Although the correlation of Hughmark appears to be the most reliable for this purpose, the correlation does not consider the effect of flow pattern and hence must at times predict α 's which are at variance with those which would actually be observed.

The high mass velocity data of Fitzsimmons is somewhat better correlated by the homogeneous model (Model E) than the slip model (Model F). However with the exception of all but a few points, the slip model correlation is adequate. The adequacy of the slip model may be attributed to the

fact that Hughmark's⁽¹⁵⁾ void fraction correlation, which was used to predict α , predicts a slip ratio which tends toward 1.0 as the mass velocity increase. Use of a void fraction correlation which ignores the effect of mass velocity on slip results in a very poor correlation of the Fitzsimmons data.

Values for the data obtained from the literature and the predictions computed by the slip and homogeneous models are tabulated in Appendix D.

3.2 Analyses of Contraction Data

By application of a one-dimensional force-momentum flux balance, an expression for the pressure drop across a contraction in two phase flow may be derived. Janssen⁽³⁾ did so and assumed that the velocity of each phase may be represented by a single average value. He also assumed, following the procedure using in analysis of pressure losses in single phase, that pressure P_3 (see Fig. 15) acts over the full area of the small pipe and that there are no frictional losses between sections 1 and 3. Under conditions where the pressure loss is a small enough fraction of the total pressure so that x may be taken as constant, Janssen⁽³⁾ obtained

$$\begin{aligned}
 P_1 - P_4 = & \frac{G_1^2}{2g_c \rho_1} \left[\frac{1}{\sigma^2} \left\{ \frac{\rho_1}{\rho_g} x^2 \bar{\alpha}_1 \left(\frac{1}{C^2 \alpha_3^2} - \frac{1}{\alpha_4^2} \right) + (1-x)^2 (1-\bar{\alpha}_1) \right. \right. \\
 & \left. \left(\frac{1}{C^2 (1-\alpha_3)^2} - \frac{1}{(1-\alpha_4)^2} \right) \right\} - \frac{2}{\sigma^2} \left\{ \frac{\rho_1}{\rho_g} x^2 \left(\frac{1}{C \alpha_3} - \frac{1}{\alpha_4} \right) + (1-x)^2 \left(\frac{1}{C (1-\alpha_3)} - \frac{1}{(1-\alpha_4)} \right) \right\} \right. \\
 & \left. + \frac{\rho_1}{\rho_g} x^2 \bar{\alpha}_2 \left(\frac{1}{\sigma^2 \alpha_4^2} - \frac{1}{\alpha_1^2} \right) + (1-x)^2 (1-\bar{\alpha}_2) \left\{ \frac{1}{\sigma^2 (1-\alpha_4)^2} - \frac{1}{(1-\alpha_1)^2} \right\} \right] \quad (8)
 \end{aligned}$$

where

G_1 = total mass velocity at section 1 lbm/ft²hr

C = vena contracta area ratio

σ = channel area ratio

x = mixture quality

$\alpha_1, \alpha_3, \alpha_4$ = void fractions at sections 1, 3 and 4

$\bar{\alpha}_1 = (\alpha_3 + \alpha_2)/2$

$\bar{\alpha}_2 = (\alpha_1 + \alpha_4)/2$

Janssen further assumed that the value of C to be used may be obtained from single phase data [Weisbach's⁽¹⁷⁾ values for single phase flow are given in Table 2] for the same area ratio.

Table 2

Contraction Coefficients for
Abrupt Contractions

σ	C_c
0.0	0.617
0.1	0.624
0.2	0.632
0.3	0.643
0.4	0.659
0.5	0.681
0.6	0.712
0.7	0.755
0.8	0.813

Use of Equation (8) requires a knowledge of x , α_1 , α_3 and α_4 . In the data obtained during the present series of tests, α_1 and α_4 were determined. Since quality was not measured directly, the value of x was determined by using Hughmark's⁽¹⁵⁾ relationship between x and α .

The value of α_3 is unknown and must be estimated. One reasonable postulate is that α_3 may be calculated as if the two phase fluid were flowing through a straight pipe having the cross sectional area of the vena contracta. The curves indicated as Model A on Figs. 4 - 7 compare this model to the contraction data of the present tests. (Note that G in Figs. 4 - 7 is based on small size pipe.) As noted previously, it appears that the model tends to underpredict the observed values, particularly at high voids. This conclusion is verified by Fig. 16 where the data of the present investigation plus the steam water data of Ferrell and McGee⁽²⁾, Fitzsimmons⁽⁵⁾, and Geiger⁽⁴⁾ are compared to the all slip model. The data are consistently underpredicted. The average fractional deviation, $\bar{d}$, is $-.177$.

Janssen⁽³⁾ observed, by means of motion pictures of a transparent abrupt contraction, that there was a strong mixing action in the area of the vena contracta. He observed the two phase flow to contract ahead of the contraction and then to form a jet which extended past the area change. He observed strong mixing action along the jet boundaries and that the two-phase mixture just past the contraction had a homogenized appearance.

These observations were confirmed by the evidence obtained from the transparent test section used to obtain data for the 0.56 area ratio. It was clear that the fluid in the area of vena contracta was much better mixed than that upstream or downstream. This can be seen in the high speed photograph shown in Fig. 17. Flow is from the larger glass pipe at the left to the smaller glass pipe at the right. The active mixing taking place immediately after the area change is clearly visible. It

Fig. 16. Comparison of Pressure Drop Predicted by Model B with the Measured Pressure Drop Across an Abrupt Contraction.

$$G = 1.1 \times 10^6 \text{ lbs/hrft}^2 \text{ (based on large pipe)}$$
$$P = 25 \text{ psig} \qquad \alpha \approx 43\%$$

Fig. 17 - High Speed Photographs of Behavior at Contraction

will also be noted that the fluid remains more homogeneous in the small size pipe than it was initially because of the higher velocity in the smaller size pipe.

Based upon his observations, Janssen⁽³⁾ postulated that complete mixing occurred ($\alpha = \alpha_{\text{homogeneous}}$) at the vena contracta. When this model was examined, it was found to be satisfactory at low voids but to overpredict the pressure drop at high voids. It was therefore postulated that less complete mixing occurred at high void fractions. The best agreement with the measured pressure drops was obtained when it was assumed that the void fraction at the vena contracta, α_3 , was given by

$$\alpha_3 = \alpha_{\text{homogeneous}}, \quad \text{for } \alpha_4 \leq 0.5 \quad (9)$$

$$\alpha_3 = \alpha_{\text{slip}} + A(\alpha_{\text{homogeneous}} - \alpha_{\text{slip}}), \text{ for } \alpha_4 > 0.5$$

where $A = 1.5 - \alpha_4$

α_{slip} = value of α which would be computed for vena contracta size pipe in absence of contraction

α_{homog} = void fraction based on slip ratio of 1.0.

This model is designated Model D and is compared to the data for the current tests in Figs. 4 - 7. It may be seen that, when appropriate allowance is made for both the possible errors in pressure drop ratio and α , essentially all data points of this investigation may be fitted by Model D.

Fig. 18 compares Model D to the present data as well as those of previous investigations^(2,4,5,6). Very good agreement is obtained. Statistical analysis of the data represented by Fig. 18 shows the average fractional deviation to be only 0.034 and $s(d) = .254$. The proposed correlation thus represents the mean of the data. From Fig. 18 we find that .95% of the data points lie between the ratios $\Delta P_m / \Delta P_{sp} = 1.4$ and $\Delta P_p / \Delta P_m = 1.4$ which is consistent with the value of $s(d)$.

If the error estimates made for the data of the present investigation may be considered typical, the $\pm 2\sigma$ error for all the data plotted may be of the order of $\pm 30\%$. One would conclude that, if such data were compared to a model which in itself was errorfree, nearly all the data should lie between the ratios $\Delta P_m / \Delta P_p = 1.3$ and $\Delta P_p / \Delta P_m = 1.43$. This is roughly consistent with the results of the statistical analysis and provides further justification for selection of this model.

Values for the data from the literature and present experiments and the predictions obtained from the various models are tabulated in Appendix D.

Geiger⁽⁴⁾ noted that his contraction data could be well described by the homogeneous model. For the data of the present investigation, values of x were obtained from the measured α via Hughmark's⁽¹⁵⁾ correlation and α_{homg} computed from these qualities assuming a slip ratio of one*. It may be seen from the curves designated Model A on Figs. 4 - 7 that the homogeneous model lies very close to Model D. Comparison of the homogeneous model to the available Freon and steam-water data in Fig. 19 shows very good agreement. Experimentally measured qualities were used

* As noted previously, the qualities computed from the heat balance are subject to large errors due to the low heat of vaporization of Freon 114.

Fig. 18. Comparison of Pressure Drop Predicted by Model D with the Measured Pressure Drop Across an Abrupt Contraction.

Fig. 19. Comparison of Pressure Drop Predicted by Model A with the Measured Pressure Drop Across an Abrupt Contraction.

for the steam-water data. The average fractional deviation, $\bar{d}$, is .028 which is only slightly higher than obtained from Model D.

The agreement of the homogeneous model with the data (particularly at low mass flows) can only be regarded as fortuitous since it clearly is not describing the actual physical process. Nevertheless, it is a very convenient design tool.

3.3 Analysis of Contraction-Expansion Combinations

The pressure loss, ΔP_{loss} , across the contraction and expansion may be obtained by the algebraic sum of the pressure changes

$$\Delta P_{\text{loss}} = \Delta P_C - \Delta P_E \quad (10)$$

We may obtain an expression for the loss by algebraically adding Equation (3) and (8). We then have

$$\begin{aligned} \Delta P_{\text{loss}} = \Delta P_{\text{loss}} = & \frac{G^2}{2\rho_1 g_c} \left[\frac{1}{\sigma^2} \left\{ \frac{\rho_1}{\rho_g} x^2 \bar{\alpha}_1 \left(\frac{1}{C^2 \alpha_3^2} - \frac{1}{\alpha_4^2} \right) + (1-x)^2 (1-\bar{\alpha}_1) \left(\frac{1}{C^2 (1-\alpha_3)^2} \right. \right. \right. \\ & \left. \left. - \frac{1}{(1-\alpha_4)^2} \right) \right\} - \frac{2}{\sigma^2} \left\{ \frac{\rho_1}{\rho_g} x^2 \left(\frac{1}{C \alpha_3} - \frac{1}{\alpha_4} - \frac{\sigma}{2\alpha_5} - \frac{\sigma^2}{2\alpha_6} \right) + (1-x)^2 \left(\frac{1}{C(1-\alpha_3)} - \frac{1}{(1-\alpha_4)} \right. \right. \\ & \left. \left. + \frac{\sigma}{2(1-\alpha_5)} - \frac{\sigma^2}{2(1-\alpha_6)} \right) \right\} + \frac{\rho_1}{\rho_g} x^2 \bar{\alpha}_2 \left(\frac{1}{\sigma^2 \alpha_4} - \frac{1}{\alpha_1^2} \right) + (1-x)^2 (1-\bar{\alpha}_2) \left\{ \frac{1}{\sigma^2 (1-\alpha_4)^2} \right. \\ & \left. \left. - \frac{1}{(1-\alpha_1)^2} \right\} \right] \quad (11) \end{aligned}$$

where

G = total mass velocity in large size pipe, lb/hr ft

C = vena contracta area ratio

α_i = void fraction at i^{th} section

$\bar{\alpha}_1 = (\alpha_3 + \alpha_4)/2$

$\bar{\alpha}_2 = (\alpha_1 + \alpha_4)/2$

and section 1 is upstream of the contraction, section 3 is at the vena

contracta, section 4 downstream of contraction, section 5 is upstream of the expansion and section 6 is downstream of the expansion. The notation does not become more compact by use of this summation since in the general case it is not known whether the expansion or contraction is upstream and no general rule for equality of α 's can be assumed.

Use of Equation (11) again requires that we assign values for α at positions 1, 3, 4, 5, and 6.

In Figs. 8 -11, the data from the present study are compared with three models, viz.

Model I - Homogeneous flow assumed.

Slip ratio of 1.0 at all locations

Model J - Slip flow everywhere. Slip ratio calculable by using

Hughmark's correlation based on straight pipe conditions.

Model K - Slip flow everywhere but at vena contracta where α is obtained from Equation (18).

It is readily apparent that Model K, which is consistent with the assumptions which led to the best separate estimate of contraction and expansion pressure changes, provides the best fit. Fig. 20 & 21 compare all the data from this investigation with that of Janssen⁽³⁾ to models I & K. Again it is clear that model K provides the best prediction of the data.

Better than 95% of the data points plotted on Fig. 20 are contained within the ratios $\Delta P_p / \Delta P_m = 1.4$ and $\Delta P_m / \Delta P_p = 1.4$. As previously noted in the discussion of the contraction data, this ratio range is roughly consistent with what might be expected on the basis of the error estimates for the present data.

Fig. 20. Comparison of Measured Ratio of Two-Phase to Single-Phase Pressure Loss Across a Long Contraction-Expansion Section With the Ratio Predicted by the Proposed Model (Model K).

Fig. 21. Comparison of Measured Ratio of Two-Phase to Single-Phase Pressure Loss Across a Long Contraction-Expansion Section With the Ratio Predicted by the Homogeneous Model (Model 1).

The general agreement between model K and the data provides confirmation that appropriate models have been chosen for both contraction and expansion. It should be noted that model K can be applied safely only to systems where the contraction and expansion are well separated. Janssen⁽³⁾ has noted that, for short inserts, less mixing is obtained at the vena contracta and somewhat lower pressure drops than predicted by model K are obtained. The data of Cermak⁽¹⁸⁾, however, do not appear to confirm this trend. These data are, however, open to questions since full pressure recovery was not obtained at the downstream measurement point. Further study of the effect of the distance between an expansion and contraction on overall Δp is required. Development of an equation specifying α at the vena contracta as a function of separation distance and α would allow a single prediction procedure to be used for all geometries.

The cumbersome nature of Equation (11) indicates the desirability of providing some simplification as an aid to the designer. This can be accomplished by noting that the homogeneous model provides a good representation of the contraction pressure drop. If homogeneous conditions are assumed, then the contraction pressure drop is given by

$$\Delta P_c = \frac{G^2}{2\sigma^2 g_c} \left[\left(\frac{1}{C} - 1 \right)^2 + (1 - \sigma)^2 \right] \left(\frac{x}{\rho_g} + \frac{1-x}{\rho_l} \right) \quad (12)$$

where G is the total mass velocity based on the cross section of the larger size pipe.

Combination of Equation (3) and (12) yield

$$\Delta P_{\text{loss}} \approx \frac{G^2}{\sigma^2 g_c \rho_1} \left\{ \frac{\rho_1}{2} \left(\frac{x}{\rho_g} + \frac{1-x}{\rho_1} \right) \left[\left(\frac{1}{C} - 1 \right)^2 + (1-\sigma)^2 \right] - \left(\frac{\rho_1}{\rho_g} x^2 \left(\frac{1}{\alpha_1 \sigma} - \frac{1}{\alpha_2} \right) \right) - [(1-x)^2 \left(\frac{1}{\sigma(1-\alpha_1)} - \frac{1}{(1-\alpha_2)} \right)] \right\} \quad (13)$$

where

α_1 = void fraction upstream of expansion

α_2 = void fraction downstream of expansion

Equations (12) and (13) may be used as convenient approximations by the designer

4.0 Conclusions and Recommendations

Correlation of the literature data for abrupt expansions shows that the data may be predicted using one dimensional momentum theory and assuming slip flow upstream and downstream of the expansion. The pressure change across the expansion may be obtained from

$$\Delta p_e = \frac{G_T^2 \sigma^2}{\rho_1 g_c} \left[\frac{\rho_1}{\rho_g} x^2 \left(\frac{1}{\alpha_1 \sigma} - \frac{1}{\alpha_2} \right) \right] + [(1-x)^2 \left(\frac{1}{\sigma(1-\alpha_1)} - \frac{1}{(1-\alpha_2)} \right)] \quad (3)$$

using α 's obtained from measured quality via Hughmark's⁽³³⁾ correlation. At low mass velocities, the homogeneous model substantially overpredicted the pressure change. This is in accord with Lottes' earlier conclusion⁽³⁰⁾. As the mass velocity is increased, the agreement is improved. The available data show the homogeneous model to provide reasonable agreement at the highest mass flow rates. This is in accord with what one would expect. Use of the homogeneous model will be discussed in the next topical report of this project.

The steam-water and freon-freon vapor data on abrupt contraction were best correlated by

$$\begin{aligned}
\Delta P_c = & \frac{G_1^2}{2g_c \rho_1} \left[\frac{1}{\sigma^2} \left\{ \frac{\rho_1}{\rho_g} x^2 \bar{\alpha}_1 \left(\frac{1}{C^2 \alpha_3^2} - \frac{1}{\alpha_4^2} \right) + (1-x)^2 (1-\bar{\alpha}_1) \right. \right. \\
& \left. \left(\frac{1}{C^2 (1-\alpha_3)^2} - \frac{1}{(1-\alpha_4)^2} \right) \right\} - \frac{2}{\sigma^2} \frac{\rho_1}{\rho_g} x^2 \left(\frac{1}{C \alpha_3} - \frac{1}{\alpha_4} \right) + (1-x)^2 \left(\frac{1}{C(1-\alpha_3)} - \frac{1}{(1-\alpha_4)} \right) \right. \\
& \left. \left. + \frac{\rho_1}{\rho_g} x^2 \bar{\alpha}_2 \left(\frac{1}{\sigma^2 \alpha_4^2} - \frac{1}{\alpha_1^2} \right) + (1-x)^2 (1-\bar{\alpha}_2) \left(\frac{1}{\sigma^2 (1-\alpha_4)^2} - \frac{1}{(1-\alpha_1)^2} \right) \right] \quad (8)
\end{aligned}$$

where α_1 and α_4 are obtained from observed values or from qualities via Hughmark's⁽¹⁵⁾ correlation. The value of α_3 is obtained from

$$\alpha_3 = \alpha_{\text{homogeneous}}, \quad \text{for } \alpha \leq 0.5$$

$$\alpha_3 = \alpha_{\text{slip}} + (\alpha_{\text{homogeneous}} - \alpha_{\text{slip}}), \quad \text{for } \alpha \geq 0.5$$

This correlation is in accord with the observations of the present investigation and those of Janssen⁽³⁾ which show a strong mixing action in the area of the vena contracta.

As noted by Geiger⁽⁴⁾ the homogeneous model was found to provide a good approximation of the contraction pressure drop throughout the full velocity range. Although the homogeneous model does not appear to be in accord with the actual physical process, it provides a convenient design tool.

Pressure drops ΔP_L , across expansion-contraction geometries (in Freon-Freon and steam-water systems) were well predicted by

$$\Delta P_L = \Delta P_c - \Delta P_e$$

where ΔP_c was obtained from Equation (8) and ΔP_e from Equation (3) following the assumptions previously indicated.

The results for expansion-contraction geometries with long separations should not be applied directly to expansion-contraction geometries in which both area changes are in close proximity. The data of Janssen⁽³⁾ indicate lower pressure drops are obtained. This effect is now being investigated and will be reported on subsequently.

The fact that the abrupt area change data for both steam-water and freon-freon vapor systems were equally well represented lends confidence to the approach used here. It appears that, with appropriate assumptions, one dimensional momentum theory is adequate for prediction of abrupt area change pressure losses in two phase flow.

References

- (1) Mendler, O., "Sudden Expansion Losses in Single and Two-Phase Flow," PhD Dissertation, U. of Pittsburgh (1963).
- (2) Ferrell, J. K. and J. W. McGee, U.S.AEC Report, "Two-Phase Flow Through Abrupt Expansions and Contractions," TID-2339-Vol. 3 (1966).
- (3) Janssen, E., "Two-Phase Pressure Loss Across Abrupt Contractions and Expansions - Steam Water and 600-1400 Psia," International Heat Transfer Conference, Vol. 5, p. 13, ASME (1966).
- (4) Geiger, G.E., "Sudden Contraction Losses in Single and Two Phase Flow," PhD Dissertation, U. of Pittsburgh (1964).
- (5) Fitzsimmons, D.E., "Two Phase Pressure Drop in Piping Components," Hanford Laboratory Report HW-80970 Rev. 1 (1964).
- (6) Janssen, E. and Kervinen, J. A., "Two-Phase Pressure Drop Across Expansions and Contractions; Water-Steam Mixtures at 600-1400 Psia," General Electric Co. Report GEAP-4622 (1964).
- (7) Collier, J. G., "Convective Boiling and Condensation," McGraw Hill (1972).
- (8) Lahey, R. T., "Two-Phase Flow in Boiling Water Nuclear Reactors," GE Report NEDO-13388 (1974).
- (9) Yadigaroglu, G., University of California at Berkeley, personal communication.
- (10) El Wakil, M. M., "Nuclear Power Engineering," p. 288, McGraw Hill, New York (1962).
- (11) Baroczy, C. J., "A Systematic Correlation for Two-Phase Pressure Drop," North American Aviation Report, NAA-SR-Memo-11858.
- (12) McMillan, H. K., "A Study of Flow Patterns and Pressure Drop in Horizontal Two Phase Flow," PhD Dissertation, Purdue University (1963).
- (13) Batchelor, G. K., "An Introduction to Fluid Mechanics," Cambridge Univ. Press, p. 374 (1967).
- (14) Lottes, P. A., Nuclear Sci. and Eng. 9, 26 (1961).
- (15) Hughmark, G. A., Chem. Eng. Prog. 58, (4), 62 (1962).
- (16) Dukler, A. E., M. Wicks, R. G. Cleveland, AIChE J. 10, 44 (1964).
- (17) Weisbach, J., "Die Experimental Hydraulic," J. S. Engelhardt, Freiberg (1855)

- (18) Cermak, J. O., J. J. Jicha, and R. G. Lightman, Trans. ASME, J. Heat Transfer, 86, 227 (1964).
- (19) Obeck, I., "Impedance Void Meter," Report KR 32 (1962).
- (20) Wamsteker, A.J.J. et al., "The Application of the Impedance Method for Transient Void Fraction Measurement and Comparison with γ -ray Attenuation Technique EUR 2030 (1965).
- (21) Cinorelli, L. and A. Premoli, Energia Nucleare 13, 12 (1966).
- (22) McManus, H. N., Fr., "An Experimental Investigation of Liquid Distribution and Surface Character in Horizontal Annular Two-Phase Flow," Interim Report OOR Project 2117, Contract DA-30-115-ORD-992 (195).

APPENDIX A

Void Meter Description and Calibration

Measurements of void fractions in the Freon 113 system were made using a sensor which detected changes in the dielectric constant of the flowing fluid. For a given fluid at a specific temperature, the capacitance between two plates immersed in the fluid is a function of the void fraction.

Capacitance, or impedance type, gauges were used as early as 1962⁽¹⁹⁾. Later studies are reported in 1965⁽²⁰⁾ and 1966⁽²¹⁾. The early gauges used two parallel plates or two concentric cylinders⁽²¹⁾. Current (1974) commercial designs use helical electrodes. The present design uses a series of vertical parallel plates. A drawing of the sensor used is shown in Fig. 22. The active portion of the unit consists of 7 plates of nickel plated copper, 1/32 in. thick and 4-1/2 in. long. The plates are spaced equally and held in place by a slotted block of Teflon having a 1 in. x 1 in. square flow passage.

The parallel plate capacitor is designed for a range of approximately 60 to 120 μpf from full void to no void. The electrical circuit used for measurement is shown in Fig. 23. The void sensor impedance plus lead and stray capacitance constitute a portion of the timing circuit for a sawtooth generator. The amplitude and the frequency of the sawtooth output of IC-1 are functions of the capacitance of the sensor and hence a function of the dielectric constant of the flowing fluid. The output of IC-1 is rectified by diode D-1 and becomes the input to a frequency sensitive filter circuit, IC-2. The output of IC-2 is a d.c. voltage proportional to measured capacitance. The output of IC-2 is amplified and filtered by IC-3 to produce

* 100-200 kHz

Fig. 22. Capacitance Type Void Sensor.

D-1, D-2 : GE A-14-A

IC-1, IC-2, IC-3 : F U6A7741393

M : 0-10 volt DC voltmeter

Fig. 23. Void Sensor Circuit

VOID SENSOR

MODEL NEL-1

a voltage in the range of 0 to 10 volts which was read on a digital voltmeter.

The dielectric constant of a liquid and its vapor are substantially different. Hence, as the void fraction changes there is an apparent change in the capacitance between two electrodes immersed in the fluid. Cimoreli and Premoli⁽⁴⁰⁾ considered the change in capacitance between two horizontal electrodes placed in the flow passage (one electrode at top of passage, one at bottom). For slug flow, two parallel paths are present and the capacitance varies linearly with the void fraction. In bubbly flow (vapor bubbles distributed in continuous liquid matrix), a nearly linear response is also predicted. For stratified flow, the liquid and vapor paths are in series and a considerably different response is obtained. A similar difficulty is encountered in annular flow. In mist flow, the fluid consists of droplets of liquid in a vapor matrix. This mixture has a highly non-linear response and leads to capacitance measurements which are lower than bubbly flow throughout the entire range.

The present design, which we have noted uses a series of vertical plates instead of two horizontal plates, eliminates some of these difficulties. The linear response of bubbly and slug flow is retained. The difficulty with stratified flow is eliminated since the orientation of the plates now provides for parallel paths rather than a series path. The response in the annular flow region is nearly linear since horizontal annular flow (in the absence of substantial entrainment) will behave much like stratified flow. Measurements of circumferential variation of film thicknesses in annular flow⁽²²⁾ have shown that the liquid film is very thin in the upper portion of the tube and nearly all of the liquid carried along the bottom of the chamber. Hence, a void fraction based on the liquid along the horizontal walls, as obtained in the present design, will be nearly correct (providing entrainment is not significant).

The difficulty with the mist flow (or near mist) pattern cannot be circumvented. The present void sensor is not recommended for service in this region. None of the data taken in this study are believed to lie in the mist flow region. It is believed that the present design may be less sensitive to changes in flow pattern than the current commercial design. The current commercial unit uses an electrode array in a helical configuration on the inside diameter of the flow tube.

Although, the dielectric constant of vapors varies very little with temperature, the dielectric constant of most liquids (including Freon 113) is sensitive to temperature. The capacitance reading when the system is full of liquid must therefore be determined for each operating temperature. The capacitance is then taken to vary linearly with α between that obtained with all liquid and that with all vapor. To avoid electronic drift, the unit is periodically calibrated against a standard capacitor during use.

The assumption of a linearity relationship between capacitance and α was shown to be true for the stratified flow pattern. With the void sensor on the bench, the level of liquid in the sensor was varied. Output was linear with liquid level and hence with void fraction (α).

To examine the behavior of the void sensor in the bubbly and slug flow pattern regions, another calibration experiment was performed. In this test, the void sensor was placed in a vertical line and a mixture of freon liquid and vapor was passed slowly upward. The upward flow, due to natural circulation was sufficiently low so that the frictional pressure drop was negligible. The pressure difference between two points on the vertical

line then allows computation of the density of the fluid in the line. The values of α obtained from these density measurements are then compared with the results obtained from the capacitance sensor*. A line diagram of the apparatus used is shown in Fig. 24.

The results of the comparison of α obtained from density and capacitance measurements are shown in Fig. 25. Open and closed points indicate data from two separate runs. The comparison is good with the disagreement being largely within the error of the experiment. These errors, whose estimated magnitude are indicated by the vertical bars in Fig. 22, arise largely because of the difficulty of completely excluding vapor from the manometer lines in the simple apparatus used for this test. It would appear that for the α 's below .35, the difference between the measurements of the two methods is less than .04.

The design of the present void sensor unit is satisfactory only with liquids having a very high resistivity. It is unsatisfactory when used with tap water. This is apparently also a characteristic of the commercial unit since the commercial unit is not recommended for water service.

A series of air-water flow tests were conducted to determine what effect the void sensor had on two-phase flow pattern. Visual observations were made in glass tubes placed upstream and downstream of the test section. It was found that there were no significant changes in flow pattern across the sensor providing the length between the air-water mixing tee and sensors was long enough to allow fully developed flow to be established. Approximately 40 inches of one in. tubing was adequate to accomplish this.

* This calibration procedure has been previously used by workers at the General Electric Co.

LEGEND

- F: 3 Necked 1-liter Flask
- HM: Heating Mantel
- V: Variac
- VS: Void Sensor
- PT: Pressure Taps Connected by Hg Manometer
- α : Power Lead to Digital Voltmeter
- WC: Water Condenser
- SF: 1-liter Separatory Funnel
- T: Thermometer
- GT: Glass Tube dia = 25 mm
- MP: Metal Pipe dia = 3/4"

Fig. 24. Voidmeter Calibration Apparatus

Fig. 25. Comparison of Void Fraction From Density and Capacitance Measurement

Appendix B

Experimental Data Tabulation and Data Reduction Procedure

Experimental Data TabulationNomenclature

ΔP_{c+St}	Measured ΔP errors contraction pressure taps (includes pipe friction)
$\Delta P_{\epsilon+c+St}$	Measured ΔP across entire test section (includes pipe function)
ϕ_{10}^2	Two phase function multiplier
ΔP_{st}	Pipe function component of contraction pressure drop measurement
ΔP_{accler}	Acceleration pressure drop
$\Delta P_{\epsilon+c}$	Pressure drop across expansion and contraction corrected for frictional and acceleration losses
$\Delta P_{\epsilon+c} *$	Pressure drop across expansion and contraction corrected for friction, acceleration and non-recovery effects
$\frac{\Delta P_{\epsilon+c} * (TP)}{\Delta P_{\epsilon+c} (SP)}$	Corrected two phase to single phase pressure drop ratio across expansion plus contraction

$\sigma = 0.56$
 $Pr = 75 \text{ psia}$
 $G = 2.4 \times 10^6$

RUN NO.	Void Fraction	ΔP_{c+St}	ΔP_{e+c+St}	ϕ_{10}^2	ΔP_{St}	ΔP_c	$\Delta P_{accel.}$	ΔP_{e+c}	ΔP_{e+c}^*	$\frac{\Delta P_{e+c_{TP}}}{\Delta P_{e+c_{CP}}}$
VII-20-1	39.0	200.0	193.0	1.5	28.0	172.0	7.2	129.7	113.25	2.46
20-2	41.0	216.0	212.0	1.52	28.4	187.6	8.18	147.02	129.63	2.81
20-3	30.0	175.0	156.0	1.31	24.5	150.5	4.16	102.84	89.4	1.94
20-4	31.5	181.0	168.0	1.39	26.0	155.0	4.56	111.44	98.4	2.14
20-6	1.5	120.0	87.0	1.0	18.7	101.3	0.0	49.6	49.6	1.08
20-7	6.0	128.0	93.5	1.19	22.25	105.7	.57	48.43	45.41	.99
20-8	18.0	147.0	128.0	1.20	22.5	124.5	2.16	80.84	74.3	1.61
20-9	27.0	162.0	147.0	1.34	25.0	137.0	3.65	93.25	82.3	1.79
20-10	37.0	187.0	193.0	1.54	28.8	158.2	5.83	129.57	119.0	2.58
21-1	42.0	224.0	218.0	1.64	30.6	193.4	8.4	148.3	129.0	2.80
21-2	49.0	259.0	259.0	1.89	35.5	223.5	12.0	176.0	149.3	3.24
21-3	51.5	274.0	280.0	2.07	37.7	236.2	13.1	191.4	163.9	3.56
21.4	54.5	306.0	302.0	2.10	39.2	266.8	15.36	208.24	169.2	3.67

$\sigma = 0.56$
 $P = 55 \text{ psia}$
 $G = 2.3 \times 10^6$

RUN NO.	Void Fraction	ΔP_{c+St}	ΔP_{e+c+St}	ϕ_{10}^2	ΔP_{St}	ΔP_c	$\Delta P_{accel.}$	ΔP_{e+c}	ΔP_{e+c}^*	$\frac{\Delta P_{e+c_{TP}}}{\Delta P_{e+c_{CP}}}$
VII-13-1	23.0	150.0	137.0	1.25	23.4	126.6	4.08	86.1	78.4	1.7
13-2	6.5	118.0	87.5	.9	16.85	101.1	.75	53.05	50.52	1.09
13-3	22.5	140.0	128.0	1.25	23.4	116.6	3.92	77.28	69.8	1.51
13-4	27.0	144.0	144.0	1.22	22.84	121.2	4.7	93.62	86.7	1.88
13-5	33.0	150.0	162.0	1.35	25.3	124.7	6.3	105.10	97.5	2.11
13-6	38.0	175.0	181.0	1.49	27.9	147.1	8.5	116.7	104.9	2.27
13-7	22.0	140.0	131.0	1.25	23.4	116.6	3.8	80.4	73.5	1.59
13-8	4.5	118.0	81.0	1.0	18.7	99.3	.63	42.9	40.5	0.88
13-9	0.0	115.0	81.0	1.0	18.7	96.3	0.0	43.6	43.6	0.94
13-10	1.5	118.0	81.0	1.0	18.7	99.3	0.0	43.6	43.6	0.94
14-1	2.5	118.0	81.0	1.0	18.7	99.3	0.0	43.6	43.6	0.94
14-2	6.5	122.0	87.5	.9	16.8	105.2	.75	53.15	50.4	1.09
14-3	8.0	128.0	93.5	.99	18.5	109.5	1.10	55.4	52.0	1.13
14-4	12.0	131.0	100.0	.99	18.5	112.5	1.88	61.12	56.0	1.21
14-5	21.5	147.0	131.0	1.28	23.96	123.0	3.8	79.3	71.6	1.55
14-6	26.0	153.0	142.0	1.20	22.5	130.5	4.7	92.3	83.9	1.82
14-7	26.0	156.0	144.0	1.20	22.5	133.5	4.7	95.3	86.9	1.88
14-8	30.0	162.0	162.0	1.26	23.6	138.4	5.6	109.2	101.0	2.19
14-9	35.0	181.0	181.0	1.40	26.2	154.8	7.1	121.5	110.4	2.39
17-3	0.0	120.0	87.5	1.0	18.7	101.3	0	50.1	50.1	1.08
17-4	0.0	115.0	82.6	1.0	18.7	96.3	0	45.2	45.2	.98
17-5	16.5	140.0	122.0	1.1	20.6	119.4	5.8	75.0	68.4	1.48
17-6	22.0	150.0	134.0	1.25	23.4	126.6	3.8	83.4	75.2	1.63
17-7	27.5	159.0	153.0	1.22	22.8	136.2	5.0	102.4	93.95	2.03
17-8	33.0	175.0	172.0	1.33	24.9	150.9	6.3	115.9	105.45	2.28

$\sigma = 0.56$
 $P = 40 \text{ psia}$
 $G = 2.5 \times 10^6$

RUN NO.	Void Fraction	ΔP_{c+St}	$\Delta P_{\epsilon+c+St}$	ϕ_{10}^2	ΔP_{St}	ΔP_c	$\Delta P_{\text{accel.}}$	ΔP_{e+c}	ΔP_{e+c}^*	$\frac{\Delta P_{\epsilon+c_{TP}}}{\Delta P_{\epsilon+c_{CP}}}$
VII-8-8	2.0	119.0	84.0	1.0	18.7	100.3	.47	46.1	45.0	.98
8-9	2.5	119.0	84.0	1.0	18.7	100.3	.47	46.1	45.0	.98
8-10	6.0	122.0	87.0	1.0	18.7	103.3	.78	48.8	46.5	1.01
9-1	11.5	128.0	100.0	1.08	20.2	107.8	1.86	57.74	53.4	1.16
9-2	12.0	131.0	103.0	1.08	20.2	110.8	1.86	60.74	56.4	1.23
9-3	21.0	144.0	125.0	1.31	24.5	119.5	3.57	72.4	64.1	1.39
9-4	22.0	147.0	134.0	1.36	25.4	121.6	3.72	79.4	71.36	1.55
9-5	26.0	153.0	147.0	1.34	25.1	127.9	4.65	92.15	84.3	1.83
9-6	29.0	156.0	156.0	1.39	26.0	130.0	5.27	98.7	90.6	1.97
9-7	32.0	162.0	165.0	1.44	26.9	135.1	6.20	104.9	95.9	2.08
9-8	34.0	169.0	175.0	1.45	27.1	141.9	6.82	113.88	104.5	2.27
9-9	34.0	172.0	181.0	1.45	27.1	144.9	6.82	119.88	111.5	2.42
9-10	37.0	175.0	187.0	1.46	27.4	147.6	7.91	124.4	115.8	2.52
10-1	38.0	175.0	187.0	1.49	27.9	147.1	8.06	123.14	113.8	2.47
10-2	41.0	184.0	202.0	1.58	29.6	154.4	9.92	132.88	123.66	2.69
10-3	44.0	194.0	217.0	1.65	30.9	163.1	12.10	143.10	13.37	2.91
10-4	46.0	200.0	230.0	1.70	31.85	168.15	13.33	152.90	144.65	3.14

$\sigma = 0.56$
 $P = 75 \text{ psia}$
 $G = 2.0 \times 10^6$

RUN NO.	Void Fraction	ΔP_{c+St}	$\Delta P_{\epsilon+c+St}$	ϕ_{lo}^2	ΔP_{St}	ΔP_c	$\Delta P_{\epsilon+c}$	$\Delta P_{\epsilon+c*}$	$\frac{\Delta P_{\epsilon+c}^{TP}}{\Delta P_{\epsilon+c}^{SP}}$
VII-18-1	6.0	93.5	72.0	1.05	15.6	77.9	40.8	39.1	1.20
18-2	12.5	96.6	81.0	1.33	19.75	76.85	41.5	38.4	1.18
18-3	18.5	109.0	103.0	1.30	19.3	89.7	64.4	60.4	1.85
18-4	27.5	125.0	125.0	1.45	21.55	103.45	82.0	76.95	2.36
18-5	30.0	125.0	128.0	1.54	22.85	105.15	82.3	76.23	2.34
18-6	35.0	137.0	137.0	1.70	25.25	111.75	86.5	77.4	2.37
18-7	43.0	156.0	175.0	1.90	28.2	127.8	118.6	114.66	3.52
18-8	46.5	175.0	187.0	2.14	31.78	143.2	123.4	113.2	3.47
18-9	51.5	202.0	212.0	2.44	36.25	165.95	139.5	129.1	3.96
18-10	54.5	231.0	218.0	2.56	38.0	193.0	142.0	112.0	3.44
19-1	59.0	244.0	268.0	2.64	39.2	204.8	189.6	177.5	5.44
19-2	5.0	87.5	68.5	1.03	15.3	72.2	37.9	36.8	1.13
19-3	17.0	106.0	100.0	1.32	19.6	86.4	60.8	57.1	1.75
19-4	32.0	137.0	137.0	1.53	22.7	114.3	91.6	85.2	2.61
19-5	43.0	168.0	181.0	1.91	28.35	139.65	124.3	117.5	3.6
19-6	53.0	215.0	225.0	2.48	36.85	178.15	151.3	135.06	6.14
19-7	48.0	197.0	200.0	2.19	32.5	164.5	135.0	119.0	3.65

$\sigma = 0.56$
 $P = 55 \text{ psia}$
 $G = 2.0 \times 10^6$

RUN NO.	Void Fraction	ΔP_{c+St}	$\Delta P_{\epsilon+c+St}$	ϕ_{lo}^2	ΔP_{St}	ΔP_c	$\Delta P_{\epsilon+c}$	$\Delta P_{\epsilon+c*}$	$\frac{\Delta P_{\epsilon+c}^{TP}}{\Delta P_{\epsilon+c}^{SP}}$
VII-12-1	1.0	81.0	62.5	1.0	14.85	66.2	32.8	32.8	1.01
12-2	1.0	81.0	62.5	1.0	14.85	66.2	32.8	32.8	1.01
12-3	4.5	90.5	65.5	1.0	14.85	75.7	35.8	34.9	1.07
12-4	8.0	87.0	68.6	1.05	15.6	71.4	37.4	35.4	1.09
12-5	11.0	93.5	75.0	1.15	17.1	76.4	40.8	37.0	1.13
12-6	16.5	96.5	87.5	1.28	19.0	77.5	49.5	45.8	1.40
12-7	18.5	100.0	93.5	1.31	19.45	80.5	54.6	50.9	1.56
12-8	19.5	103.0	100.0	1.33	20.0	83.0	60.0	56.1	1.72
15-1	2.0	84.5	59.5	1.0	14.8	69.7	29.9	29.9	.92
15-2	3.0	87.0	62.5	1.0	14.8	72.2	32.9	32.9	1.01
15-3	5.5	90.5	68.5	1.02	15.1	75.4	38.3	37.4	1.15
15-4	9.5	93.5	71.8	1.1	16.3	77.2	39.2	36.4	1.12
15-5	10.5	93.5	75.0	1.13	16.8	76.7	41.4	38.6	1.18
15-6	14.0	100.0	81.0	1.21	18.0	82.0	45.0	40.8	1.25
15-7	42.0	150.0	172.0	1.8	26.8	123.2	118.4	116.3	3.57
15-8	21.0	109.0	103.0	1.36	20.2	88.8	62.6	58.1	1.78
15-9	36.5	137.0	146.0	1.62	24.0	113.0	98.0	92.8	2.85
15-10	16.5	101.0	93.5	1.29	19.1	82.0	55.3	52.6	1.61
16-1	0.0	81.0	59.5	1.0	14.85	66.2	29.8	29.8	.91
16-2	0.0	83.0	62.5	1.0	14.85	69.2	32.8	32.8	1.01
16-3	12.5	96.5	81.0	1.15	17.1	79.4	46.8	43.6	1.34
16-4	34.0	131.0	140.0	1.58	23.5	107.5	93.0	88.8	2.72
16-5	32.0	131.0	124.0	1.53	22.7	108.3	79.1	70.6	2.17
16-6	6.5	87.0	65.5	1.07	15.9	71.1	33.7	31.8	.98
16-7	20.0	103.0	100.0	1.34	19.9	83.1	60.2	56.6	1.74
16-8	36.5	138.0	147.0	1.66	24.6	113.4	97.8	92.2	2.84
16-9	42.0	150.0	172.0	1.84	27.3	122.7	117.4	115.2	3.53
16-10	45.0	172.0	187.0	1.97	29.2	142.8	128.6	121.5	3.73
17-1	48.0	181.0	206.0	2.06	30.6	150.4	144.8	142.0	4.36

$\sigma = 0.56$
 $P = 40 \text{ psia}$
 $G = 2.0 \times 10^6$

RUN NO.	Void Fraction	ΔP_{c+St}	$\Delta P_{\epsilon+c+St}$	ϕ_{lo}^2	ΔP_{St}	ΔP_c	$\Delta P_{\epsilon+c}$	$\Delta P_{\epsilon+c*}$	$\frac{\Delta P_{\epsilon+c} TP}{\Delta P_{\epsilon+c} SP}$
VII-4-6	2.3	93.5	62.5	1.02	15.13	78.37	32.24	32.24	.99
4-7	19.0	112.0	106.0	1.37	20.32	91.68	65.35	61.07	1.87
4-8	21.5	115.0	112.0	1.35	20.10	94.9	71.9	67.9	2.08
4-9	25.2	121.0	122.0	1.44	21.37	99.63	79.3	74.5	2.29
4-10	27.0	125.0	128.0	1.53	22.7	102.3	82.6	77.7	2.38
5-1	30.0	134.0	140.0	1.59	23.6	110.4	92.8	87.9	2.7
5-2	37.0	146.0	162.0	1.65	24.5	121.5	113.0	110.2	3.38
5-3	40.0	150.0	162.0	1.76	26.1	123.9	109.8	104.1	3.19
7-1	9.5	90.5	68.6	1.08	16.02	74.48	36.56	33.7	1.03
7-2	12.0	96.5	81.0	1.07	15.8	80.7	49.25	46.18	1.42
7-3	2.0	84.0	62.5	1.02	15.13	68.9	32.23	32.2	.99
7-4	6.0	87.5	65.5	1.00	14.80	72.7	35.8	35.8	1.10
7-5	25.0	115.0	118.0	1.5	22.2	92.8	73.5	69.3	2.13
7-6	29.0	125.0	131.0	1.53	22.7	102.3	85.6	81.2	2.49
7-7	40.0	150.0	165.0	1.76	26.1	123.9	112.8	108.2	3.32
7-8	40.0	143.0	156.0	1.76	26.1	116.9	112.8	110.9	3.40
7-9	42.0	150.0	172.0	1.82	27.0	123.0	118.0	115.8	3.55
7-10	50.0	156.0	178.0	1.9	28.2	127.8	121.6	118.6	3.64
8-1	47.0	162.0	187.0	2.0	30.0	132.0	127.7	125.48	3.85
8-2	49.0	168.0	206.0	2.09	31.0	137.0	144.0	144.0	4.42
8-3	52.0	175.0	208.0	2.38	35.3	139.7	137.0	135.3	4.15
8-4	60.0	209.0	274.0	3.00	44.5	164.5	185.0	185.0	5.67

$\sigma = 0.56$
 $P = 30 \text{ psia}$
 $G = 2.0 \times 10^6$

RUN NO.	Void Fraction	ΔP_{c+St}	$\Delta P_{\epsilon+c+St}$	ϕ_{lo}^2	ΔP_{St}	ΔP_c	$\Delta P_{\epsilon+c}$	$\Delta P_{\epsilon+c*}$	$\frac{\Delta P_{\epsilon+c+TP}}{\Delta P_{\epsilon+c+SP}}$
VII-1-5	6.0	87.3	65.4	1.08	16.1	71.2	33.3	32.8	1.01
1-6	41.0	130.9	168.4	2.0	29.8	101.1	108.35	108.3	3.32
1-7	34.0	137.2	149.7	2.0	29.8	107.4	90.3	85.1	2.61
1-8	32.0	137.2	143.4	1.85	27.6	109.6	87.8	81.3	2.49
1-9	38.0	146.5	162.1	1.95	29.08	117.4	103.8	98.4	3.02
1-10	30.0	124.7	137.2	1.7	25.3	99.4	86.3	82.8	2.54
2-1	5.0	84.2	65.5	1.0	14.9	69.3	35.7	34.8	1.07
2-2	8.0	87.3	65.5	1.2	17.9	69.4	29.7	27.8	.85
2-3	11.0	93.5	71.7	1.2	17.9	75.6	35.8	32.7	1.0
2-4	14.0	102.9	93.5	1.32	19.7	83.2	54.1	50.5	1.55
2-5	22.0	109.1	118.5	1.64	24.4	84.7	70.1	67.4	2.67
2-6	35.0	130.9	149.7	1.90	28.3	102.5	93.3	90.3	2.77
2-7	33.0	130.9	149.7	1.90	28.3	102.5	93.3	90.3	2.77
2-8	37.0	140.3	155.9	1.90	28.3	111.9	99.3	94.5	2.90
2-9	38.0	140.3	159.0	1.94	29.0	111.3	101.0	97.0	2.98
2-10	38.0	140.3	162.1	1.94	29.0	111.3	104.0	101.6	3.12
3-1	41.0	146.6	171.5	2.0	29.8	116.8	112.4	110.5	3.39
6-1	3.0	84.2	62.3	1.0	14.9	69.3	32.6	31.3	.96
6-2	5.0	87.3	62.3	1.0	14.9	72.4	32.6	31.4	.96
6-3	9.0	87.3	67.0	1.16	17.3	70.0	32.4	32.0	.98
6-4	12.0	90.4	71.7	1.23	18.3	72.1	34.9	31.7	.97
6-5	16.0	96.7	109.1	1.30	19.4	77.3	70.2	69.3	2.13
6-6	20.0	106.0	112.2	1.43	21.3	84.7	69.5	66.9	2.05
6-7	28.0	124.7	130.9	1.78	26.6	98.1	77.8	72.7	2.23
6-8	36.0	137.2	155.0	1.97	29.3	107.9	97.1	93.4	2.87
6-9	45.0	155.9	180.8	2.16	32.2	123.7	116.4	112.9	3.46

$\sigma = 0.25$
 $P = 65 \text{ psia}$
 $G = 1.6 \times 10^6$

RUN NO.	Void Fraction	ΔP_{c+St}	$\Delta P_{\epsilon+c+St}$	ϕ_{lo}^2	ΔP_{St}	ΔP_c	$\Delta P_{\epsilon+c}$	$\frac{\Delta P_{\epsilon+c_{TP}}}{\Delta P_{\epsilon+c_{SP}}}$	Flow Pattern
V-8-3	2.0	53.0	46.9	1.0	7.8	45.2	35.2	1.09	Bubbly
8-4	6.0	61.0	53.0	1.07	8.35	52.6	40.48	1.25	Bubbly
8-5	23.0	65.5	70.0	1.405	10.96	54.5	53.56	1.65	Bub-An
8-6	34.0	85.8	89.0	1.75	13.7	72.2	68.45	2.11	Froth-An
8-7	41.0	96.8	100.0	1.90	14.8	82.0	77.8	2.50	Froth-An
8-8	26.0	67.5	75.0	1.48	11.5	56.0	57.75	1.78	Froth-An
8-9	11.0	53.0	57.0	1.16	9.05	44.0	43.43	1.34	Bubbly
8-10	3.0	59.4	46.9	1.0	7.8	51.6	35.2	1.09	Bubbly
9-3	10.0	48.4	56.2	1.16	9.05	39.4	42.6	1.31	Froth-An
9-4	6.0	46.8	53.0	1.07	8.35	38.5	40.48	1.25	Froth-An
9-5	12.0	53.0	57.7	1.20	9.36	43.6	43.6	1.35	Froth-An
12-4	4.0	64.0	54.6	1.0	7.8	56.2	42.9	1.32	Bubbly
12-5	15.0	59.4	62.5	1.25	9.75	49.6	47.8	1.48	Froth
12-6	32.0	84.4	86.0	1.80	14.0	70.4	65.0	2.01	Froth-An
12-7	44.0	106.0	108.0	1.90	14.8	91.2	85.8	2.65	Froth-An
12-8	57.0	129.5	143.0	2.68	20.9	110.0	111.6	3.44	Froth-An

$\sigma = 0.25$
 $P = 65 \text{ psia}$
 $G = 1.1 \times 10^6$

RUN NO.	Void Fraction	ΔP_{c+St}	$\Delta P_{\epsilon+c+St}$	ϕ_{10}^2	ΔP_{St}	ΔP_c	$\Delta P_{\epsilon+c}$	$\frac{\Delta P_{\epsilon+c_{TP}}}{\Delta P_{\epsilon+c_{SP}}}$	Flow Pattern
V-6-1	11.0	28.1	31.2	1.25	3.38*	24.7	26.13	1.11	Wavy
6-2	23.4	40.5	40.5	1.40	3.78*	36.7	34.8	1.47	Wavy
6-3	13.5	29.6	31.2	1.30	3.51*	26.1	25.94	1.10	Wavy
6-4	1.0	29.6	29.6	1.0	3.86	25.75	23.8	1.01	Bubbly
6-6	20.0	32.6	34.4	1.35	3.65*	28.95	28.93	1.23	Wavy
6-7	4.5	23.4	28.0	1.10	2.97*	20.43	23.55	1.00	Wavy
6-8	6.0	25.0	28.0	1.15	3.11*	21.9	23.34	1.00	Wavy
6-9	15.0	28.1	31.2	1.35	3.65*	24.45	25.73	1.09	Wavy
6-10	44.0	59.6	65.5	2.80	10.8	48.8	49.3	2.09	Froth-An
7-1	14.0	28.1	31.2	1.30	3.51*	24.5	25.94	1.10	Wavy
7-2	5.0	25.0	28.0	1.10	2.97*	22.03	23.55	1.00	Wavy
7-3	18.0	29.6	32.8	1.37	3.70*	25.9	27.25	1.15	Wavy
7-4	9.0	25.0	28.0	1.20	3.24*	21.8	23.14	.98	Wavy
7-5	37.0	53.0	50.0	1.90	5.13*	47.9	42.3	1.79	Wavy
7-6	44.0	64.0	65.5	2.20	8.5	55.5	52.7	2.23	Wavy An
7-7	51.5	78.0	81.0	2.60	10.04	68.0	65.94	2.79	Wavy An
7-8	62.0	104.0	106.0	3.50	13.5	90.5	85.7	3.63	Wavy An
7-9	66.0	121.0	123.0	6.0	15.44	105.6	100.0	6.24	Annular
7-10	59.5	90.5	90.5	3.30	12.74	77.8	71.5	3.03	Annular
8-1	54.5	84.0	86.0	3.0	11.58	72.5	68.7	2.91	Annular
8-2	51.0	76.4	76.5	2.6	10.04	66.4	61.5	2.61	Annular
13-1	20.0	31.2	36.0	1.85	5.0*	26.2	28.5	1.21	Wavy

* Corrected using $\Delta P_{St} = .7 * \phi_{10}^2$

$\sigma = 0.25$
 $P = 40 \text{ psia}$
 $G = 1.6 \times 10^6$

RUN NO.	Void Fraction	ΔP_{c+St}	$\Delta P_{\epsilon+c+St}$	ϕ_{lo}^2	ΔP_{St}	ΔP_c	$\Delta P_{\epsilon+c}$	$\frac{\Delta P_{\epsilon+c_{TP}}}{\Delta P_{\epsilon+c_{SP}}}$	Flow Pattern
V-3-1	12.0	53.0	56.0	1.3	8.65*	44.35	43.0	1.33	Wavy
3-2	3.5	59.3	46.8	1.0	9.50	49.8	32.55	1.00	Bubbly
3-3	7.0	46.8	50.0	1.1	7.32*	39.48	39.02	1.20	Wavy
3-4	0.0	54.5	43.6	1.0	9.5	45.0	29.35	.91	SP
3-5	0.0	53.0	43.6	1.0	9.5	43.5	29.35	.91	SP
3-6	2.3	53.0	46.8	1.0	9.5	43.5	32.55	1.00	Bubbly
3-7	8.0	46.8	53.0	1.2	7.98*	38.8	41.0	1.27	Wavy
4-1	0.0	56.1	43.6	1.0	9.5	46.6	29.35	.91	SP
4-2	0.9	57.7	46.8	1.0	9.5	48.2	32.55	1.0	Bubbly
4-3	1.9	59.2	46.8	1.01	9.6	49.6	32.55	1.0	Bubbly
4-4	5.9	46.8	51.5	1.07	7.12*	39.68	40.8	1.26	Wavy
4-5	11.8	51.5	57.6	1.21	8.05*	43.45	45.5	1.60	Wavy
4-6	16.0	57.6	60.8	1.39	9.24*	48.36	46.94	1.45	Wavy
4-7	19.0	59.4	62.5	1.50	9.98*	49.42	47.5	1.47	Wavy
4-8	20.0	62.4	65.5	1.50	14.25	48.15	44.13	1.36	Ann
4-9	26.0	72.0	75.0	1.65	15.7	56.3	51.45	1.59	Ann
5-1	2.5	59.2	48.4	1.0	9.5	49.7	34.15	1.05	Bubbly
5-2	8.0	48.4	53.0	1.12	7.45*	40.95	41.83	1.29	Wavy
5-3	17.2	56.3	59.2	1.40	13.3	43.0	39.25	1.21	Wav-An
5-4	12.0	53.0	57.6	1.2	11.4	41.6	40.50	1.25	Wav-An
5-5	17.2	57.6	60.8	1.41	13.4	44.2	40.7	1.26	Wav-An
5-6	25.5	68.6	71.6	1.65	15.7	52.9	48.05	1.48	Annular
11-6	1.0	62.4	50.0	1.0	9.5	52.9	35.75	1.10	Bubbly
11-7	4.0	65.5	53.0	1.06	10.07	55.43	37.9	1.17	B-Wav
16-1	2.0	59.3	50.0	1.0	9.5	49.8	35.75	1.10	Bubbly
16-2	4.0	59.3	46.9	1.06	10.07	49.23	31.8	.98	Bubbly

* Corrected $\Delta P_{St} = 0.7 * \phi_{lo}^2$
homo.

$\sigma = 0.25$
 $P = 40 \text{ psia}$
 $G = 1.1 \times 10^6$

$[\Delta P_{\text{loss}}^{\text{SP}} = 20.5]$

RUN NO.	Void Fraction	$\Delta P_{\text{c+St}}$	$\Delta P_{\text{ε+c+St}}$	ϕ_{lo}^2	ΔP_{St}	ΔP_{c}	$\Delta P_{\text{ε+c}}$	$\frac{\Delta P_{\text{ε+c}}^{\text{TP}}}{\Delta P_{\text{ε+c}}^{\text{SP}}}$	Flow Pattern
V-1-1	13.0	25.0	29.6	1.32	4.6*	20.4	22.7	1.14	Wavy
1-2	2.8	25.0	29.6	1.07	3.5*	21.5	24.3	1.19	Wavy
1-3	26.5	37.4	40.5	1.80	6.3*	31.1	31.05	1.51	
1-4	46.0	65.5	62.5	2.35	12.20	53.3	44.5	2.17	Wavy-An
1-5	8.5	25.0	29.5	1.20	3.8*	21.2	23.8	1.16	Wavy
1-6	26.0	37.4	40.5	1.80	6.7*	30.7	30.45	1.49	Wavy
1-7	13.4	26.5	31.2	1.33	4.95*	21.55	23.78	1.16	Wavy
1-8	6.2	23.4	28.1	1.17	4.36*	19.04	21.56	1.05	Wavy
1-9	22.5	31.2	34.4	1.73	6.44*	24.8	24.74	1.21	Wavy
1-10	30.0	62.0	45.2	1.88	9.7	32.3	30.0	1.46	St-An
2-1	2.0	23.4	28.0	1.04	5.4	18.0	20.0	.98	Bubbly
2-2	4.5	23.4	28.0	1.11	4.13*	19.27	21.81	1.06	Wavy
2-3	9.0	21.8	28.8	1.20	4.47*	17.33	22.1	1.08	Wavy
2-4	17.0	28.0	31.2	1.50	5.58*	22.42	22.8	1.11	Wavy
2-7	49.0	70.0	73.4	2.65	13.7	56.3	53.0	2.59	Annular
2-8	15.0	26.5	32.8	1.45	5.40*	21.1	24.7	1.20	Wavy
2-9	41.0	59.0	62.4	2.2	11.4	47.6	45.5	2.27	St-Ann
2-10	49.0	71.5	72.0	2.65	13.76	57.74	51.36	2.51	Annular
18-1	1.2	28.0	28.0	1.01	5.24	22.76	20.14	.98	Bubbly
18-2	8.0	23.4	28.0	1.18	6.13	17.27	18.8	.92	Slug
18-3	5.5	21.8	28.0	1.14	5.92	15.88	19.12	.93	Slug
18-4	11.0	25.0	28.0	1.22	4.54*	20.46	21.19	1.03	Wavy
18-5	12.5	26.5	28.0	1.30	4.84*	21.66	20.74	1.01	Wavy
18-6	20.0	29.6	32.8	1.70	6.33*	23.27	23.3	1.14	Wavy
18-7	44.0	57.6	62.5	2.30	11.94	45.66	44.6	2.18	W-An
18-8	56.0	78.0	82.7	3.05	15.83	62.17	59.0	2.88	Annular

$\sigma = 0.25$
 $P = 40 \text{ psia}$
 $G = 1.1 \times 10^6$

$[\Delta P_{\text{loss}} \text{ SP} = 20.5]$

RUN NO.	Void Fraction	ΔP_{c+St}	$\Delta P_{\epsilon+c+St}$	ϕ_{lo}^2	ΔP_{St}	ΔP_c	$\Delta P_{\epsilon+c}$	$\frac{\Delta P_{\epsilon+c_{TP}}}{\Delta P_{\epsilon+c_{SP}}}$	Flow Pattern
V-1-1	13.0	25.0	29.6	1.32	4.6*	20.4	22.7	1.18	Wavy
1-2	2.8	25.0	29.6	1.07	3.5*	21.5	24.3	1.19	Wavy
1-3	26.5	37.4	40.5	1.80	6.3*	31.1	31.05	1.51	Wavy
1-4	46.0	65.5	62.5	2.35	12.20	53.3	44.5	2.17	Wavy-An
1-5	8.5	25.0	29.5	1.20	3.8*	21.2	23.8	1.16	Wavy
1-6	26.0	37.4	40.5	1.80	6.7*	30.7	30.45	1.49	Wavy
1-7	13.4	26.5	31.2	1.33	4.95*	21.55	23.78	1.16	Wavy
1-8	6.2	23.4	28.1	1.17	4.36*	19.04	21.56	1.05	Wavy
1-9	22.5	31.2	34.4	1.73	6.44*	24.8	24.74	1.21	Wavy
1-10	30.0	42.0	45.2	1.88	9.7	32.3	30.0	1.46	St.-An
2-1	2.0	23.4	28.0	1.04	5.4	18.00	20.0	.98	Bubbly
2-2	4.5	23.4	28.0	1.11	4.13*	19.27	21.81	1.06	Wavy
2-3	9.0	21.8	28.8	1.20	4.47*	17.33	22.1	1.08	Wavy
2-4	17.0	28.0	31.2	1.50	5.58*	22.42	22.8	1.11	Wavy
2-7	49.0	70.0	73.4	2.65	13.7	56.3	53.0	2.59	Annular
2-8	15.0	26.5	32.8	1.45	5.40*	21.1	24.7	1.20	Wavy
2-9	41.0	59.0	62.4	2.2	11.4	47.6	45.5	2.22	St-An
2-10	49.0	71.5	72.0	2.65	13.76	57.74	51.36	2.51	Annular
18-1	1.2	28.0	28.0	1.01	5.24	22.76	20.14	.98	Bubbly
18-2	8.0	23.4	28.0	1.18	6.13	17.27	18.8	.92	Slug
18-3	5.5	21.8	28.0	1.14	5.92	15.88	19.12	.93	Slug
18-4	11.0	25.0	28.0	1.22	4.54*	20.46	21.19	1.03	Wavy
18-5	12.5	26.5	28.0	1.30	4.84*	21.66	20.74	1.01	Wavy
18-6	20.0	29.6	32.8	1.70	6.33*	23.27	23.3	1.14	Wavy
18-7	44.0	57.6	62.5	2.30	11.94	45.66	44.6	2.18	W-An
18-8	56.0	78.0	82.7	3.05	15.83	62.17	59.0	2.88	An

$\sigma = 0.25$
 $P = 30 \text{ psia}$
 $G = 1.5 \times 10^6$

RUN NO.	α	ΔP_{c+St}	$\Delta P_{\epsilon+c+St}$	ϕ_{lo}^2	ΔP_{St}	ΔP_c	$\Delta P_{\epsilon+c}$	$\frac{\Delta P_{\epsilon+c_{TP}}}{\Delta P_{\epsilon+c_{SP}}}$
IV-7-2	0.5	46.7	39.0	1.0	7.5	39.2	27.3	1.0
7-4	3.6	53.0	43.6	1.2	9.0	44.0	29.6	1.08
7-5	5.0	39.0	45.2	1.2	6.3*	32.7	39.4	1.44
7-7	15.3	51.4	56.2	1.4	10.5	40.9	39.8	1.46
7-8	16.6	51.4	56.2	1.5	11.25	40.15	39.8	1.46
8-4	0.5	46.7	39.0	1.0	7.5	39.2	27.3	1.0
8-5	2.4	48.3	42.2	1.1	8.25	40.05	29.3	1.07
8-6	2.6	49.9	43.7	1.1	8.25	41.65	30.8	1.13
8-7	15.8	48.3	51.5	1.4	10.5	37.8	35.0	1.28
9-2	3.3	37.4	42.2	1.0	7.5	29.9	30.5	1.12
9-3	7.2	35.8	42.2	1.25	6.55*	29.25	36.4	1.33
9-4	14.4	46.7	48.4	1.35	7.09*	39.61	42.5	1.56
9-5	8.1	37.4	42.2	1.25	6.56*	30.84	36.3	1.33
9-6	10.8	39.0	43.7	1.3	6.83*	32.17	37.8	1.38
9-7	10.9	40.5	45.3	1.3	6.83*	33.67	39.4	1.44
9-8	20.1	53.0	56.2	1.6	8.40*	44.6	44.5	1.63
9-9	10.0	37.4	42.2	1.3	6.83*	30.57	36.4	1.33

SINGLE PHASE PRESSURE DROP MEASUREMENTS

σ	Pressure	G	$\Delta P_{c_{SP}}$	$\Delta P_{\epsilon+c_{SP}}$ (PSF)
0.56	75 psia	2.4×10^6	95.5	46.04
0.56	75 psia	2.0×10^6	66.8	32.6
0.56	55 psia	2.5×10^6	94.0	46.1
0.56	55 psia	2.0×10^6	64.0	32.5
0.56	40 psia	2.5×10^6	100.0	46.0
0.56	40 psia	2.0×10^6	64.0	32.6
0.56	30 psia	2.0×10^6	66.8	32.6
0.25	65 psia	1.6×10^6	45.4	32.3
0.25	65 psia	1.1×10^6	26.25	23.58
0.25	40 psia	1.6×10^6	45.4	32.33
0.25	40 psia	1.1×10^6	26.3	20.50
0.25	30 psia	1.5×10^6	39.0	27.30

Appendix B
Experimental Data Tabulation and Data Reduction Procedure

I. Data Reduction Procedure

The data reduction scheme used will be illustrated by means of Run No. V-8-7.

(1) Calculation of Mass Flow

This measurement was taken using an orifice plate which was installed in between the pump and the immersion heaters. The flow through the orifice was liquid Freon and computed from

$$W = C A_2 \sqrt{2g_c \Delta P \rho_L}$$

Since the ΔP was measured in units of inches of water.

$$\Delta P = \rho_w \Delta H_w g/g_c$$

where ΔH_w is the distance between the two water columns in the manometer.

ρ_w is the density of water

A_2 for the orifice used was equal to .0064

C was supplied by the manufacturer for the range of operation and was equal to .685.

Upon insertion of the above constants and conversion factors, the mass flow rate equation becomes

$$W = .0801 \sqrt{\rho_{\text{Freon}} * \Delta H_w}$$

For the present run:

ΔH_w was held constant at

$$\Delta H_w = 10'' \text{ of water}$$

$$\rho_{\text{Freon}} = 91 \text{ lb ft}^3$$

$$W = 0.801 (910)^{1/2}$$

$$= 2.416 \text{ lb/Sec.}$$

(2) Pressure Drop Across Abrupt Contraction

2.a

The measured value for contraction included pressure loss due to straight pipe friction.

The differential pressure was measured by using a Honeywell multiple range ΔP cell. The scale of the meter was set to measure 0 to 30 inches of water.

The reading for the present run was 62% of full scale or $.62 \times 30$ inch of water = 18.6 in. of water.

Also 1" of water = 5.197 PSF

$\therefore$ 18.6" of water = 96.8 PSF

Hence $\Delta P_{\text{cont}} + \Delta P_{\text{St}} = 96.8 \text{ PSF}$

2.b Estimation of Straight Pipe Friction Losses

$$\Delta P_{\text{TP}} = \Delta P_{\text{SP}} * \phi_{10}^2$$

where ΔP_{TP} is the pressure drop for two phase

ΔP_{SP} is the pressure drop for single phase

ϕ_{10}^2 is the two phase friction multiplier

2.b.1 Calculation of Single Phase Straight Pipe Friction Losses

$$\Delta P_{\text{SP}} = f \frac{L}{D} \frac{G^2}{2fg_c}$$

In this test section, two pipe diameters were used,

Pipe No. 1 L = 1 ft. D = 1"

Pipe No. 2 L = 2 ft. D = 2"

Hence $\Delta P = \Delta P_1 + \Delta P_2$

$$\underline{\underline{\Delta P_1}} = f * 12 * \frac{G^2}{2 * 85.5 * 32.17}$$

where $G = \frac{\dot{m}}{\text{Area}} = \frac{2.416 * 4}{\pi * (1/12)^2} = 443.189 \frac{\text{lbm}}{\text{ft}^2 \text{sec}}$

$$\Delta P_1 = f * \frac{12 * (443.19)^2}{2 * 85.5 * 32.17} = 428.46 * f$$

For the calculation of f , a Reynolds No. will have to be estimated,

$$\text{Reynolds No.} = \frac{GD}{\mu}$$

$$\mu = \frac{1.1}{3600} = 3.05 * 10^{-4} \frac{\text{lb}}{\text{ft sec}}$$

$$\text{Reynolds No.} = \frac{443.19 * 10^4}{12 * 3.05} = 1.2 * 10^5$$

For smooth pipe,

$$f = .017$$

Hence $\Delta P_1 = 428.46 * .018 = 7.27 \text{ psf}$

$$\Delta P_2 = \frac{f * 12 * (G_2^2)}{2 * 85.5 * 32.17} = \frac{f * 12 * (443.19 * 25)^2}{2 * 85.5 * 32.17} = 26.77 f$$

$$\text{Reynolds No.} = \frac{GD}{\mu}$$

$$= \frac{110.8 * 2 * 10^4}{12 * 3.05} = 6 * 10^4$$

$$f = .02$$

$$\Delta P_2 = 26.77 * .02 = .535$$

$$\Delta P_{Sp} = 7.27 + .535 = 7.8 \text{ PSF}$$

2.b.2 Calculation of ϕ_{10}^2

The Baroczy correlation was used for the calculation ϕ_{10}^2

From Hughmark correlation, quality for this no. was calculated to be equal to 2.09%

$$\text{Property Index } (\mu_l/\mu_g)^{0.2}/(P_2/P_g) = 0.05$$

Using Baroczy's Fig. 5

$$\phi_{10}^2 \text{ for } G = 1 \times 10^6 = 2.2$$

Correction factor for $G = 1.6 \times 10^6$ was found to be .86

$$\phi_{10}^2 = 2.2 \times .86 = 1.9$$

Hence

$$\Delta P_{St_{ST}} = 1.9 \times 7.8 = 14.8 \text{ PSF}$$

Hence

$$\Delta P_{cont} = 96.8 - 14.8 = 82.0$$

(3) Pressure Drop Across Abrupt Expansion and Contraction

3.a Differential cell reading = 64%

$$\text{Hence } \Delta P_{\epsilon+c+St} = 100.0 \text{ PSF}$$

3.b Estimation of Straight Pipe Friction Loss

The straight pipe in this measurement was

1" pipe: 18" length, 1" diameter

4 ft. long, 2" diameter

Straight Pipe Friction $\approx 1.5 \times$ St. Pipe Friction in Contraction

$$\text{Hence } \Delta P_{St_{TP}} = 1.5 \times 14.8 = 22.2 \text{ PSF}$$

$$\text{Hence } \Delta P_{etc} = 100 - 22.2 = 77.8 \text{ PSF}$$

(4) Estimation of Void Fraction

As previously noted, the void fraction was measured by using a capacitance type void sensor. The meter was calibrated to give 0 → 10 voltage difference when the void was ranged from 0 to 100%.

To correct for the variation of the zero void reading with temperature, temperature and voltage readings were taken with liquid Freon flowing through the sensor. The voltage reading was assumed to vary linearly with void between the zero void and 100% void readings (see Appendix A for void meter calibration). With these assumptions, the void fraction was determined to be 41% for the run.

(5) Correction for Vaporization

Void fraction measurements indicate no significant vaporization across the test section at low mass velocities. Therefore no flashing correction was made to the preceding sample run. At the highest mass velocity's, flashing gives rise to an acceleration term which should be subtracted from the measured data in order to get the pressure drop due to area changes and straight pipe friction losses.

6.a Considering Run No. VII-20-2

$$\Delta P_{\epsilon+St+Accler.} = 212.0$$

$\Delta P_{Straight}$ was calculated in the manner illustrated with Run No. V-8-7.

$$\Delta P_{St} = 56.8$$

$$\Delta P_{\epsilon+c+Accler.} = 212 - 56.8 = 155.2$$

6.b Calculation of Acceleration Pressure Drop

Making a force and momentum balance, we get,

$$\Delta P_{ac} A_c = \int \frac{V_e}{g_c} - m_t \frac{V_i}{g_c}$$

$$\text{or } \Delta P_a = \frac{G}{g_c} (V_e - V_i)$$

where V_e is the exit velocity of the mixture, ft/sec

V_i is the inlet velocity of the mixture, ft/sec

Also, if ρ_e is the average density of exit mixture

and ρ_i is the average density of inlet mixture

$$\text{then } V_e = \frac{G}{\rho_e}$$

$$V_i = \frac{G}{\rho_i}$$

$$\text{hence } \Delta P_a = \frac{G^2}{g_c} (1/\rho_e - 1/\rho_i)$$

$$= \frac{G^2}{g_c} (v_e - v_i)$$

where v_e and v_i are exit and inlet specific densities of the two phase mixture

For this run,

$$\alpha_{\text{inlet}} = 35\% \quad \rho_g = 1.748 \text{ Nom/ft}^3$$

$$\alpha_{\text{exit}} = 41\% \quad \rho_f = 86.06$$

$$\begin{aligned} \rho_{\text{exit}} &= \alpha_e \rho_g + (1-\alpha_e) \rho_f \\ &= .7254 + 50.344 = 51.069 \end{aligned}$$

$$\begin{aligned} \rho_{\text{inlet}} &= \alpha_i \rho_g + (1-\alpha_i) \rho_f \\ &= .61185 + 55.938 = 56.54985 \end{aligned}$$

$$\Delta P_a = \frac{G^2}{g_c} [.01958 - .01768]$$

G can be calculated for this case by following the path of calculation #1.

G in this case was calculated to be 1.34×10^6 Nom/hr ft²

$$\Delta P_a = (1.34 \times 10^6 / 3600)^2 \cdot 1/32.17 [0.00190]$$

$$= 8.18 \text{ PSF}$$

$$\text{Hence } \Delta P_{e+c} = 155.2 - 8.18$$

$$= 147.02$$

(7) Correction for Undeveloped Expansion Pressure Loss

The pressure tap after expansion section was at $L/D = 6.0$. Mendler's experimental data shows that at $L/D = 6.0$ the expansion pressure rise has not reached its fully developed value. The actual pressure rise across the expansion can be estimated by using this Mendler's data.

$$\text{For Run No. VII-20-2, } \Delta P_{etc} = \Delta P_c - \Delta P_\epsilon$$

$$\Delta P_\epsilon - \Delta P_c - \Delta P_{\epsilon+c}$$

$$= 187.6 - 147.02$$

$$= 40.58$$

$$\text{For } \alpha = 41\%$$

$$\frac{\Delta P_\epsilon \text{ at } L/D = 6}{\Delta P_{\epsilon \text{ fully developed}}} = 0.7$$

$$\Delta P_{\epsilon \text{ fully developed}} = 57.97$$

$$\Delta P_{\epsilon+c}^+ = 147.02 - 57.91 + 40.58$$

$$= 129.63$$

$$\Delta P_{\epsilon+c}^+ = 129.63$$

Appendix C - Error AnalysisI. Error Computation1. Instrument AccuracyDifferential Pressure Cell

Meter Face Output	$\pm 3\%$	full scale (2σ , from lit.)
Reading Error	$\pm .25\%$	full scale (2σ , an est.)
Fluctuations	$\alpha < 25\% \pm .25\%$	full scale (2σ , an est.)
	$\alpha > 25\% \pm 1.0\%$	full scale (2σ , an est.)

For test section #1, full scale = 20 in H_2O

For test section #2, full scale = 60 in H_2O

For 60" H_2O in full scale = 312.12 prf.

Meter Face Error = 9.36 PSF (2σ)

Reading Error = .78 PSF (2σ)

Fluctuation $\alpha < 25\% = .78$ PSF (2σ)

Then,

$$\alpha < 25\%; \sigma = \sqrt{(9.36/2)^2 + (.78/2)^2 + (.78/2)^2} = 4.712 \text{ or } 2\sigma = 9.42 \text{ PSF}$$

$$\alpha > 25\%; \sigma = \sqrt{(9.36/2)^2 + (.78/2)^2 + 3.12/2)^2} = 4.949 \text{ or } 2\sigma = 9.90 \text{ PSF}$$

For 20" H_2O in full scale = 104.04 PSF

Meter Face Error = 3.12 PSF (2σ)

Reading Error = .26 PSF (2σ)

Fluctuation $\alpha < 25\% = .26$ PSF (2σ)

$\alpha > 25\% = 1.04$ PSF (2σ)

Then,

$$\alpha < 25\%; \sigma = \sqrt{(3.12/2)^2 + (.26/2)^2 + (.26/2)^2} = 1.571 \text{ PSF}$$

$$\alpha > 25\%; \sigma = \sqrt{(3.12/2)^2 + (.26/2)^2 + (1.04/2)^2} = 1.650 \text{ PSF}$$

Flow Meter

Orifice Calibration $\pm 1.0\%$ of full scale for range used (est. of 2σ)

Meter Face Output $\pm 2.0\%$ of full scale for range used (est. of 2σ)

Reading Error $\pm .4\%$ of full scale for range used (est. of 2σ)

Fluctuation $\pm .4\%$ of full scale for range used (est. of 2σ)

$$\sigma = \sqrt{.0100^2 + .002^2 + .002^2 + .0050^2} \quad \sigma = 1.15\% \text{ of full scale}$$

Void Sensor

Void Fraction Error Freon Calibrator = $\pm .05$ (2σ)

Readout Error ≈ 0 (digital voltmeter used)

Readout Fluctuation $\approx \pm .02$

$$\sigma = \sqrt{(.025)^2 + (.01)^2} = .027 \quad (2.7\%)$$

Temperatures

a) Test Section

Thermometer Error $\pm 1\%$ of full scale (from lit.- σ)

Reading Error 10°F (σ est.)

Fluctuations 0%

Since thermometer max. is 220°F , then 1% error = 2.2°F , so

$$\sigma = \sqrt{2.2^2 + 1^2} = 2.4^\circ\text{F}$$

b) Fluid Temperature at Flow Meter

Thermometer Error $\pm 1\%$ of full scale (est. = σ)

Reading Error $\pm 1^\circ\text{F}$ (est. = σ)

Fluctuation Error 0%

Since thermometer max. is 300°F , then 1% = 3.0°F so

$$\sigma = \sqrt{3^2 + 1^2} = 3.2^\circ\text{F}$$

Density error due to 3°F error $\approx 0.3\%$ error in ρ

System Pressure

Gage Error $\pm \frac{1}{2}\%$ of full scale (σ from lit.)

Reading Error $\pm \frac{1}{2}$ psi (est σ)

Fluctuation $\pm \frac{1}{2}$ psi (est σ)

Since max gage reading is 150 psi, then $\frac{1}{2}\%$ is .75 psi, so

$$\sigma = \sqrt{.75^2 + .5^2 + .5^2} = 1.0 \text{ psi } (\sigma)$$

2. Accuracy of Results including Propagation of Error

Flow

At 140°F (typical) ρ_l (for Freon 113) = 92.33 and at full scale, which is 100" H₂O, then

$$\text{Flow} = .080145 \sqrt{\rho_l} \times 100'' \text{ H}_2\text{O} = 7.70 \text{ lb}_m/\text{sec}$$

For $\sigma = 1.15\%$ of full scale

$$\sigma = .089 \text{ lb/sec}$$

$$\text{at } 5'', \text{ flow} = 1.72 \text{ lb}_m/\text{sec} \pm .089 \quad \sigma = 5.2\%$$

$$7\frac{1}{2}'' \text{ flow} = 2.11 \text{ lb}_m/\text{sec} \pm .089 \quad \sigma = 4.2\%$$

$$10'' \text{ flow} = 2.44 \text{ lb}_m/\text{sec} \pm .089 \quad \sigma = 3.6\%$$

Note: Addition of the error in flow due to temperature measurement does not significantly change the above.

Pressure Ratio

In computing the error which may appear in the pressure ratio, consideration must be given not only to the pressure drop errors but those due to flow measurement. The pressure ratio is computed assuming a main flow rate which may be in error. The pressure ratio σ is then obtained by taking the square root of the sum of the squares of the pressure errors introduced by the flow and pressure drop measurement.

For example, for a flow indication of 5 in H_2O with 60" Water full scale in D/P cell we have

At zero voids	Mean Press, Ratio = 1.0	$\sigma = .266$	2σ error = 53%
At $\alpha = 30\%$	Mean Press, Ratio = 1.0	$\sigma = .266$	2σ error = 50%
At $\alpha = 60\%$	Mean Press, Ratio = 3.22	$\sigma = .30$	2σ error = 36.5%

For the same flow indication, but 20" water full scale on D/P cell, we have,

at zero voids	Mean Press, Ratio = 1.0	$\sigma = .12$	2σ error = 24%
At $\alpha = 30\%$	Mean Press, Ratio = 1.64	$\sigma = .166$	2σ error = 20.2%
At $\alpha = 60\%$	Mean Press, Ratio = 3.22	$\sigma = .289$	2σ error = 18.0%

Similar calculations were performed for the other flow rates used. The results are summarized in the section which follows.

It should be noted that vapor and liquid density variation introduced by pressure and temperature errors were found to have a negligible effect on the pressure ratio.

II. Summary of Results

Test Section #1 Area Ratio = .25

TYPICAL ERRORS FOR VARIOUS CONDITIONS

Mass Flow Rate (G) $\text{lb}_m/\text{ft}^2 \text{ hr}$	Associated Errors			
	Flow Error (2σ) lb_m/hr	Pressure Ratio Error (2σ)		
		$\alpha = 0\%$	$\alpha \approx 30\%$	$\alpha \approx 60\%$
1.1×10^6	$\pm 10.4\%$	$\pm 24\%$	$\pm 20\%$	$\pm 18\%$
1.4×10^6	$\pm 8.4\%$	$\pm 21\%$	$\pm 18\%$	$\pm 17\%$
1.6×10^6	$\pm 7.2\%$	$\pm 17\%$	$\pm 16\%$	-

Test Section #2 Area Ratio = .56

TYPICAL ERRORS FOR VARIOUS CONDITIONS

Mass Flow Rate (G) $\text{lb}_m/\text{ft}^2 \text{ hr}$	Associated Errors			
	Flow Error (2σ) lb_m/hr	Pressure Ratio Error (2σ)		
		$\alpha = 0\%$	$\alpha \approx 30\%$	$\alpha \approx 60\%$
2.0×10^6	$\pm 10.4\%$	$\pm 53\%$	$\pm 37\%$	$\pm 24\%$
2.5×10^6	$\pm 8.4\%$	$\pm 41\%$	$\pm 27\%$	$\pm 20\%$
2.9×10^6	$\pm 7.2\%$	$\pm 33\%$	$\pm 21\%$	-

Appendix D

Comparison of Measured Data with Analytical Predictions

Table D-1 Abrupt Expansion Data

Table D-2 Abrupt Contractor Data

Table D-3 Expansion-Constriction Data

TABLE D -1

Abrupt Expansion Data

G (lbs/hrs ft²) is based on small size pipe
P = pressure (psia)

Model E - Homogeneous Flow

Model F - Slip Flow

Model G - Slip Flow in Large Pipe,
Homogeneous Flow in Small
Pipe

** FERRELL'S EXPANSION DATA **

SYSTEM: STEAM/WATER

ORIENTATION: VERTICAL

X	ΔP	ΔP	ΔP	ΔP
QUALITY	EXP.	MODEL E	MODEL F	MODEL G
	(PSF)	(PSF)	(PSF)	(PSF)

SIG = 0.608

P = 58.

G = 0.400E 06

0.061	13.0	43.0	15.0	-32.6
0.100	25.9	69.5	23.2	-55.4
0.150	49.0	103.5	36.5	-78.1
0.200	85.0	137.5	53.4	-92.4
0.029	7.2	21.3	9.0	-12.0
0.013	1.4	10.4	5.7	-2.4

SIG = 0.608

P = 238.

G = 0.400E 06

0.007	4.3	2.9	2.5	1.9
0.022	4.3	5.5	4.0	1.3
0.065	8.6	12.9	7.1	-2.9
0.105	13.0	19.7	9.7	-7.5
0.169	17.3	30.7	14.2	-13.6
0.221	25.9	39.7	18.5	-16.8

SIG = 0.546

P = 118.

G = 0.731E 05

0.030	21.6	41.6	23.8	-0.9
0.042	27.4	56.0	29.3	-7.5
0.082	47.5	103.8	47.0	-30.9
0.110	66.2	137.4	60.2	-45.5
0.156	106.6	192.4	84.8	-63.4
0.017	14.4	26.0	17.2	5.0
0.229	203.0	279.8	133.3	-72.5

SIG = 0.546

P = 119.

G = 0.145E 07

0.013	47.5	84.1	62.0	30.0
-------	------	------	------	------

0.026	77.8	145.8	93.2	17.2
0.039	116.6	207.4	122.0	-2.0
0.076	299.5	382.8	203.8	-61.0

SIG = 0.546
P = 119.
G = 0.182E 07

0.011	85.0	117.1	90.2	50.8
0.020	126.7	184.0	127.1	43.4
0.037	142.6	310.5	191.0	13.4

SIG = 0.608
P = 118.
G = 0.400E 06

0.036	7.2	14.0	7.2	-4.7
0.073	11.5	26.8	11.3	-15.2
0.096	14.4	34.7	13.9	-21.4
0.147	23.0	52.2	20.4	-33.3
0.017	4.3	7.5	4.8	0.0
0.216	38.9	76.0	31.2	-43.8
0.268	54.7	93.9	41.2	-47.0
0.015	4.3	6.8	4.5	0.4
0.304	69.1	106.3	49.1	-46.8

SIG = 0.608
P = 118.
G = 0.796E 05

0.001	10.1	7.8	7.5	6.9
0.013	11.5	24.2	17.2	4.7

X	Δ P	Δ P	Δ P	Δ P
QUALITY	EXP.	MODEL E	MODEL F	MODEL G
	(PSF)	(PSF)	(PSF)	(PSF)
0.023	25.9	37.8	23.6	-2.0
0.035	34.6	54.2	30.3	-12.3
0.071	47.5	103.3	49.4	-46.7
0.105	63.4	149.7	68.2	-77.2
0.128	82.1	181.1	82.2	-95.1

SIG = 0.608
P = 119.
G = 0.994E 05

0.010	24.5	31.4	23.9	10.2
0.019	36.0	50.5	33.6	2.9
0.026	44.6	65.4	40.4	-4.9
0.042	57.6	99.5	54.9	-25.7
0.076	69.1	171.8	85.1	-72.7

*** MENJLER'S EXPANSION DATA ***

SYSTEM: STEAM/WATER

ORIENTATION: VERTICAL

G	X	ΔP	ΔP	ΔP	ΔP
MASS FLOW	QUALITY	EXP.	MODEL E	MODEL B	MODEL C
(LBM/SQFT.HR)		(PSF)	(PSF)	(PSF)	(PSF)

SIG = 0.145
P = 200.

2.01	0.060	114.0	185.7	113.2	97.0
2.09	0.050	110.0	171.3	108.5	94.4
2.65	0.052	109.0	284.9	184.7	161.4
3.05	0.050	96.0	364.8	242.4	213.4
3.16	0.048	90.0	378.1	254.0	224.4
3.57	0.048	325.0	482.6	329.4	292.1
2.06	0.095	220.0	295.3	169.3	140.7
2.59	0.094	289.0	462.3	277.5	233.7
2.10	0.134	304.0	437.9	248.1	204.0

SIG = 0.145
P = 400.

2.05	0.055	77.0	102.6	74.5	68.1
2.61	0.047	110.0	147.8	112.0	103.7
2.63	0.039	109.0	131.3	102.4	95.8
3.06	0.047	123.0	203.2	155.6	144.4
3.53	0.047	216.0	270.4	209.1	194.4
2.14	0.088	93.0	163.2	109.7	97.6
2.65	0.079	169.0	228.8	159.8	143.8
2.88	0.065	89.0	230.8	167.3	152.5
3.02	0.068	226.0	263.0	190.3	173.1
3.07	0.082	247.0	316.7	223.3	201.2
2.10	0.107	128.0	185.7	120.8	106.3
4.16	0.032	233.0	287.3	236.2	223.8

SIG = 0.145
P = 600.

2.03	0.046	65.0	66.9	54.2	51.4
2.06	0.044	72.0	67.0	54.7	51.9

G	X	ΔP	ΔP	ΔP	ΔP
MASS FLOW	QUALITY	EXP.	MODEL E	MODEL 3	MODEL C
(LBM/SQFT.HR)		(PSF)	(PSF)	(PSF)	(PSF)
2.54	0.044	92.0	101.8	83.8	79.7
2.59	0.037	92.0	95.4	80.4	76.9
3.10	0.053	140.0	171.0	138.5	131.0
3.69	0.044	204.0	214.9	179.8	171.4
3.72	0.053	210.0	246.2	201.5	190.7
3.94	0.044	229.0	245.0	205.6	196.1
3.94	0.048	226.0	258.9	215.0	204.4
4.10	0.049	259.0	284.1	235.8	224.1
4.12	0.046	263.0	275.5	230.4	219.5
2.07	0.098	82.0	119.2	86.1	78.7
2.48	0.094	118.0	165.6	122.1	112.1
2.57	0.089	114.0	170.5	127.0	117.1
3.06	0.083	169.0	229.1	174.7	161.9
2.04	0.138	128.0	152.8	105.0	94.3

SIG = 0.264
P = 200.

1.02	0.043	43.0	56.2	34.6	25.2
1.01	0.046	53.0	58.4	35.3	25.3
1.53	0.049	52.0	141.4	88.3	64.4
2.00	0.045	109.0	224.7	147.1	111.3
2.50	0.046	148.0	357.7	239.5	183.5
1.03	0.091	69.0	111.2	58.4	35.6
1.55	0.094	154.0	259.5	145.2	93.6
1.02	0.134	101.0	156.4	78.3	44.8
1.03	0.169	148.0	198.8	99.2	56.5

SIG = 0.264
P = 400.

1.01	0.043	35.0	32.5	23.8	20.0
1.02	0.042	35.0	32.6	24.0	20.3
1.03	0.041	35.0	32.7	24.2	20.5
1.53	0.045	78.0	77.1	57.5	48.6
1.53	0.049	74.0	82.1	50.3	50.4
2.00	0.045	112.0	131.8	99.9	85.1
2.03	0.045	123.0	135.8	103.0	87.8
2.54	0.040	172.0	195.4	153.0	133.1
1.03	0.091	49.0	61.0	38.5	28.8
1.52	0.085	79.0	125.4	83.2	64.3

G	X	ΔP	ΔP	ΔP	ΔP
MASS FLOW	QUALITY	EXP.	MODEL E	MODEL B	MODEL C
(LRM/SQFT.HR)		(PSF)	(PSF)	(PSF)	(PSF)
1.01	0.144	62.0	87.4	51.0	35.4
1.02	0.148	74.0	91.4	53.2	36.8
1.02	0.173	84.0	105.2	60.2	41.1
1.03	0.166	82.0	103.4	59.4	40.7
1.03	0.171	90.0	106.2	60.9	41.6

SIG = 0.264
P = 600.

1.02	0.044	37.0	25.7	20.5	18.3
1.56	0.046	76.0	61.9	50.0	44.6
1.97	0.045	107.0	97.4	79.5	71.5
1.99	0.045	102.0	99.3	81.3	73.0
2.51	0.046	147.0	160.3	132.1	118.8
1.03	0.089	58.0	42.9	30.4	24.9
1.50	0.086	83.0	88.7	64.7	53.9
1.03	0.132	63.0	58.8	38.9	30.3
1.03	0.181	74.0	77.0	48.7	36.6

SIG = 0.493
P = 200.

0.52	0.044	14.0	19.2	11.2	2.4
0.52	0.046	14.0	19.9	11.5	2.2
1.02	0.048	51.0	79.4	48.8	13.5
1.03	0.046	51.0	78.1	48.4	14.3
0.52	0.094	33.0	37.6	18.3	-2.7
0.52	0.115	32.0	45.3	21.3	-4.7
0.52	0.118	35.0	46.4	21.8	-5.0
0.52	0.175	43.0	67.4	30.9	-8.5
0.52	0.174	45.0	67.0	30.7	-8.5

SIG = 0.493
P = 400.

0.52	0.043	12.0	11.1	7.9	4.4
1.03	0.042	43.0	42.8	31.9	19.4
1.03	0.043	41.0	43.5	32.3	19.4
0.52	0.138	32.0	28.7	16.1	2.2
0.52	0.180	40.0	36.5	19.8	1.7

G	X	P	P	P	P
MASS FLOW	QUALITY	EXP.	MODEL E	MODEL B	MODEL C
(LRM/SQFT.HR)		(PSF)	(PSF)	(PSF)	(PSF)
0.52	0.182	35.0	36.9	17.9	1.6
0.52	0.137	33.0	28.5	16.0	2.3

SIG = 0.493
P = 500.

0.53	0.185	27.0	26.7	10.2	4.8
0.52	0.037	16.0	7.8	6.3	4.6
0.52	0.137	29.0	19.9	12.6	4.6
0.51	0.190	35.0	25.3	15.3	4.4

* * J A N S S E N ' S E X P A N S I O N D A T A * *

* SYSTEM: STEAM/WATER *

* ORIENTATION: HORIZONTAL *

G	X	ΔP	ΔP	ΔP	ΔP
MASS FLOW	QUALITY	EXP.	MODEL E	MODEL F	MODEL G
(LBM/SEC, HR)		(PSF)	(PSF)	(PSF)	(PSF)

SIG = 0.492

P = 1000.

1.02	0.204	51.1	67.9	49.0	27.7
1.03	0.305	69.8	95.8	67.3	35.9
1.03	0.379	84.8	115.2	81.4	44.8
1.02	0.504	127.3	147.2	108.2	67.6
1.02	0.608	150.5	174.5	135.1	96.0
1.03	0.696	178.7	200.4	163.4	129.0
1.02	0.812	221.6	227.8	199.8	177.9
1.02	0.899	249.3	251.9	232.9	223.1
2.06	0.095	125.3	157.3	129.5	96.2
2.06	0.184	200.7	260.2	198.3	124.2
2.05	0.289	304.0	363.9	269.8	158.1
2.05	0.387	381.0	468.5	349.3	209.3
2.05	0.437	480.0	565.2	431.5	276.7
2.05	0.570	593.3	681.9	523.3	365.6

SIG = 0.326

P = 1000.

0.78	0.051	7.5	13.9	11.9	10.8
0.78	0.097	18.4	20.2	15.9	13.4
0.78	0.194	31.0	33.5	23.9	18.4
1.55	0.048	84.9	53.0	46.6	42.7
1.55	0.075	89.1	80.2	65.0	55.7
2.33	0.046	130.0	117.7	104.8	96.8
2.33	0.032	73.2	100.4	92.1	86.9

SIG = 0.326

P = 1400.

0.78	0.051	13.0	11.8	10.7	10.0
0.77	0.106	15.0	16.2	13.6	12.1
0.79	0.192	24.2	24.9	19.5	16.4

SIG = 0.326

P = 600.

0.78	0.099	16.6	30.2	20.8	15.0
0.78	0.200	31.0	54.3	33.7	22.1

SIG = 0.197

P = 1000.

1.15	0.054	22.3	22.6	19.4	18.4
1.16	0.111	35.6	34.8	27.2	24.8
2.55	0.045	126.9	100.6	89.7	86.1
2.58	0.058	141.8	117.2	102.1	97.1
1.29	0.134	79.9	65.9	48.1	42.6

SIG = 0.132

P = 1000.

0.96	0.050	1.6	10.8	9.3	9.0
0.96	0.097	5.5	15.9	12.5	11.7
0.96	0.198	10.9	26.7	19.0	17.6
1.93	0.093	68.3	62.5	50.9	48.0
1.93	0.047	41.0	43.0	37.8	36.0

FITZSIMMONS EXPANSION DATA

SYSTEM: STEAM/WATER

ORIENTATION: VERTICAL

X QUALITY	ΔP FXP. (PSF)	ΔP MODEL E (PSF)	ΔP MODEL F (PSF)	ΔP MODEL G (PSF)
SIG = 0.620 P = 1200. G = 0.646E 07				
0.008	510.2	581.3	572.8	555.0
0.025	646.4	717.7	688.2	625.1
0.035	732.7	804.8	760.5	665.0
0.054	863.4	953.2	881.9	726.5
0.071	978.7	1095.9	997.4	779.9

SIG = 0.620 P = 1200. G = 0.485E 07				
0.022	356.1	390.4	374.8	342.3
0.043	437.3	497.4	453.6	382.3
0.083	590.7	657.0	595.2	441.1
0.121	770.2	843.0	731.6	488.9
0.165	969.5	1038.4	883.2	539.1

SIG = 0.620 P = 1200. G = 0.323E 07				
0.021	145.0	172.2	164.8	149.8
0.062	237.6	255.1	229.6	177.0
0.105	337.7	341.1	293.9	190.0
0.143	387.5	417.7	350.3	209.6
0.187	462.1	506.7	415.9	225.3

SIG = 0.444 P = 1200. G = 0.400E 07				
0.005	246.3	224.5	222.0	219.5
0.010	260.4	239.4	234.5	229.4

X	ΔP	ΔP	ΔP	ΔP
QUALITY	EXP.	MODEL E	MODEL F	MODEL G
	(PSF)	(PSF)	(PSF)	(PSF)
0.021	313.6	277.0	265.3	253.3
0.030	330.4	304.1	287.2	269.7
0.041	368.0	342.6	317.8	291.8
0.052	394.7	377.6	345.1	310.9
0.061	427.4	406.4	367.3	326.2
0.072	459.7	440.0	393.1	343.5

SIG = 0.444
P = 1200.
G = 0.300E 07

0.016	159.5	146.3	141.2	136.0
0.037	199.2	184.6	171.5	158.1
0.060	245.9	225.7	202.9	179.4
0.080	279.0	262.8	230.5	197.2
0.101	315.7	301.4	258.7	214.6
0.120	343.9	335.7	283.5	229.6
0.140	386.6	372.8	310.3	245.5
0.160	422.9	408.5	336.0	260.8

SIG = 0.444
P = 1200.
G = 0.200E 07

0.021	75.3	68.9	65.6	62.4
0.040	92.4	84.4	77.5	70.6
0.061	104.0	101.6	90.2	78.8
0.081	121.3	117.5	101.5	85.6
0.098	137.6	131.1	111.2	91.2
0.117	151.6	146.7	122.0	97.4
0.139	160.8	164.9	134.5	104.3
0.152	170.3	175.1	141.5	108.1
0.186	210.7	202.7	160.6	118.6

TABLE D-2

Abrupt Contraction Data

G = (lbs/hr ft²) based on small size pipe
P = pressure (psia)

Model A - Homogeneous Flow

Model B - Slip Flow

Model D - Slip Flow Upstream and
Downstream with Mixing
at Vena Contracta

C O N T R A C T I O N D A T A
 F R O M P R E S E N T I N V E S T I G A T I O N
 S Y S T E M) F R E O N - 1 1 3 / F R E O N - 1 1 3
 O R I E N T A T I O N) H O R I Z O N T A L

S I G = 0 . 5 6

X QUALITY	ALPHA	ΔP EXP. (PSF)	ΔP MODEL A (PSF)	ΔP MODEL B (PSF)	ΔP MODEL D (PSF)
--------------	-------	-----------------------------	--------------------------------	--------------------------------	--------------------------------

P = 30.00
 G = .20E+07

.001	.061	71.2	52.4	51.5	52.3
.010	.412	101.1	99.4	84.7	100.1
.007	.341	107.4	84.7	75.0	84.7
.007	.320	109.6	81.2	72.6	81.1
.009	.382	117.4	92.8	80.4	93.1
.006	.301	99.4	78.1	70.4	77.9
.001	.053	69.3	51.8	51.1	51.7
.001	.080	69.4	53.8	52.6	53.7
.002	.111	75.6	56.3	54.6	56.2
.002	.140	83.2	58.9	56.5	58.7
.004	.220	84.7	67.2	62.7	66.9
.008	.353	102.6	87.0	76.5	87.1
.007	.329	102.5	82.6	73.5	82.5
.009	.370	111.9	90.2	78.7	90.4
.009	.382	111.3	92.8	80.4	93.1
.009	.382	111.3	92.8	80.4	93.1
.010	.412	116.8	99.4	84.7	100.1
.000	.030	69.3	50.2	49.8	50.2
.001	.052	72.4	51.7	51.0	51.6
.001	.092	70.0	54.7	53.3	54.6
.002	.122	72.1	57.3	55.3	57.1
.003	.161	77.3	60.9	58.0	60.7
.003	.200	84.7	65.0	61.0	64.7
.005	.280	98.1	75.0	68.2	74.7
.008	.361	107.9	88.6	77.6	88.7
.013	.454	123.7	110.7	91.9	112.3

P = 40.00
 G = .20E+07

.000	.023	78.4	50.7	50.4	50.6
------	------	------	------	------	------

(CONTD...)

X QUALITY	ALPHA	ΔP EXP. (PSF)	ΔP MODEL A (PSF)	ΔP MODEL B (PSF)	ΔP MODEL D (PSF)
.004	.193	91.7	65.3	61.6	65.0
.005	.217	94.9	67.9	63.5	67.7
.006	.257	99.6	72.9	67.2	72.7
.007	.273	102.3	75.1	68.7	74.9
.008	.305	110.4	79.9	72.1	79.8
.012	.371	121.5	91.7	80.2	91.9
.014	.405	123.9	99.0	85.1	99.5
.002	.092	74.5	55.8	54.4	55.6
.003	.123	80.9	58.4	56.4	58.2
.000	.023	68.9	50.7	50.4	50.6
.001	.061	72.7	53.4	52.5	53.3
.006	.249	92.8	71.8	66.4	71.6
.008	.289	102.3	77.4	70.4	77.2
.014	.405	123.9	99.0	85.1	99.5
.014	.405	116.9	99.0	85.1	99.5
.015	.422	123.0	103.1	87.8	103.9
.019	.473	132.0	117.7	97.1	119.7
.020	.491	137.0	123.5	100.8	126.2
.023	.517	139.7	133.4	106.8	136.5
.035	.600	164.5	175.8	131.7	178.1
.021	.500	127.8	126.6	102.7	129.7

P= 55.00

G= .20E+07

.000	.011	66.2	50.4	50.3	50.4
.000	.011	66.2	50.4	50.3	50.4
.001	.046	75.7	52.8	52.1	52.7
.002	.084	71.4	55.7	54.4	55.5
.003	.112	76.4	57.9	56.2	57.7
.005	.166	77.5	62.9	60.0	62.7
.006	.186	80.5	65.0	61.5	64.7
.006	.194	83.0	65.8	62.2	65.6
.001	.023	69.7	51.2	50.9	51.1
.001	.031	72.2	51.7	51.3	51.6
.001	.054	75.4	53.3	52.6	53.2
.003	.096	77.2	56.6	55.2	56.5
.003	.108	76.7	57.6	55.9	57.4
.004	.139	82.0	60.3	58.0	60.1
.020	.423	123.2	103.5	88.5	104.3
.007	.210	88.8	67.6	63.5	67.3

(CONTD...)

X QUALITY	ALPHA	ΔP EXP. (PSF)	ΔP MODEL A (PSF)	ΔP MODEL B (PSF)	ΔP MODEL D (PSF)
.015	.364	113.0	90.5	79.8	90.7
.005	.166	82.0	62.9	60.0	62.7
.004	.123	79.4	58.9	56.9	58.7
.014	.339	107.5	85.9	76.6	85.9
.013	.323	108.3	83.1	74.7	83.0
.002	.069	71.1	54.5	53.5	54.4
.006	.202	83.1	66.7	62.8	66.4
.015	.364	113.4	90.5	79.8	90.7
.020	.423	122.7	103.5	88.5	104.3
.023	.450	142.8	110.8	93.3	112.1
.027	.483	150.4	120.8	99.7	123.1

P= 75.00
Q= .20E+07

.002	.061	77.9	53.7	52.9	53.6
.005	.123	76.8	58.7	56.7	58.5
.008	.186	89.7	64.6	61.3	64.4
.014	.274	103.4	75.1	69.0	74.9
.016	.299	105.2	78.6	71.5	78.5
.020	.348	111.7	86.7	77.2	86.7
.029	.432	127.8	104.5	89.3	105.5
.034	.466	143.2	113.9	95.5	115.6
.044	.519	165.9	131.5	106.8	134.4
.050	.547	193.0	142.6	113.8	145.4
.062	.593	204.8	165.9	128.0	168.1
.002	.054	72.2	53.1	52.4	53.1
.007	.171	86.4	63.0	60.1	62.8
.017	.315	114.3	81.1	73.3	81.0
.029	.432	139.6	104.5	89.3	105.5
.046	.528	178.1	135.0	109.0	137.9
.037	.484	164.5	119.2	99.0	121.4

CONTRACTION DATA FROM PRESENT INVESTIGATION

SYSTEM) FREON-113/FREON-113

ORIENTATION) HORIZONTAL

SIG = 0.25

Y QUALITY	ALPHA	ΔP EXP. (PSF)	ΔP MODEL A (PSF)	ΔP MODEL B (PSF)	ΔP MODEL D (PSF)
--------------	-------	-----------------------------	--------------------------------	--------------------------------	--------------------------------

P= 65.00
G= .16E+07

.001	.017	45.2	46.0	45.8	46.0
.002	.059	52.6	48.7	47.9	48.6
.009	.224	54.5	62.4	58.3	62.2
.015	.331	72.2	75.6	67.8	75.7
.021	.399	82.0	87.3	75.8	87.9
.010	.250	56.0	65.2	60.4	65.0
.003	.105	44.0	51.9	50.4	51.8
.001	.030	51.6	46.8	46.4	46.8
.003	.098	39.4	51.3	50.0	51.2
.002	.059	38.5	48.7	47.9	48.6
.004	.113	43.6	52.5	50.9	52.4
.001	.040	56.2	47.4	47.0	47.4
.005	.146	49.6	55.1	52.9	55.0
.014	.314	70.4	73.2	66.1	73.2
.024	.433	91.2	94.4	80.5	95.4
.043	.556	110.0	131.6	103.9	135.4

P= 65.00
G= .11E+07

.003	.107	24.7	26.0	25.3	26.0
.009	.229	36.7	31.6	29.3	31.5
.004	.132	26.1	27.0	26.0	27.0
.007	.196	29.0	29.9	28.1	29.8
.001	.043	20.4	23.8	23.5	23.8
.002	.058	22.0	24.3	23.9	24.3
.005	.147	24.5	27.7	26.5	27.6
.025	.432	48.8	47.7	40.2	48.3
.005	.135	24.5	27.1	26.1	27.1
.002	.049	22.1	24.0	23.7	24.0
.006	.174	26.0	28.9	27.4	28.8
.003	.088	22.0	25.3	24.7	25.3

X QUALITY	ALPHA	ΔP EXP. (PSF)	ΔP MODEL A (PSF)	ΔP MODEL B (PSF)	ΔP MODEL D (PSF)
.018	.361	47.9	40.6	35.6	40.8
.025	.432	55.5	47.7	40.2	48.3
.035	.505	68.0	57.8	46.4	59.4
.056	.605	90.5	79.4	58.9	81.9
.069	.644	105.6	92.0	65.8	94.3
.050	.580	77.8	72.9	55.2	75.3
.040	.534	72.5	62.8	49.4	65.0
.034	.499	66.4	56.8	45.8	58.3
.007	.196	26.3	29.9	28.1	29.8

P= 40.00

G= .16E+07

.000	.008	48.1	45.0	44.9	45.0
.000	.017	49.7	45.5	45.3	45.5
.001	.052	39.7	47.7	47.0	47.6
.002	.106	43.5	51.5	50.0	51.4
.003	.144	48.3	54.5	52.3	54.3
.004	.175	49.4	57.1	54.3	57.0
.004	.182	48.2	57.8	54.7	57.6
.006	.238	56.3	63.4	58.9	63.3
.000	.022	49.8	45.8	45.6	45.8
.001	.074	40.9	49.2	48.2	49.1
.003	.157	43.0	55.5	53.1	55.4
.002	.106	41.6	51.5	50.0	51.4
.003	.156	44.2	55.5	53.0	55.3
.006	.235	52.8	63.1	58.6	63.0
.000	.011	52.9	45.2	45.1	45.2
.001	.039	55.4	46.9	46.4	46.8
.000	.017	40.8	45.5	45.3	45.5
.001	.039	49.3	46.9	46.4	46.8
.001	.039	50.0	46.9	46.4	46.8
.001	.072	37.4	49.1	48.1	49.0
.002	.109	38.9	51.7	50.1	51.6
.004	.175	49.7	57.1	54.3	57.0
.008	.287	60.5	69.4	63.1	69.3
.002	.109	44.4	51.7	50.1	51.6
.001	.028	49.8	46.2	45.9	46.2
.001	.063	39.5	48.4	47.6	48.4
.000	.010	43.5	45.1	45.0	45.1
.001	.074	38.8	49.2	48.2	49.1

P= 40.00

G= .11E+07

.002	.118	20.4	26.2	25.3	26.2
------	------	------	------	------	------

X QUALITY	ALPHA	ΔP EXP. (PSF)	ΔP MODEL A (PSF)	ΔP MODEL B (PSF)	ΔP MODEL D (PSF)
.000	.025	21.5	23.0	22.9	23.0
.006	.245	31.1	32.3	29.7	32.2
.015	.433	53.3	48.0	40.0	48.6
.001	.076	21.2	24.7	24.2	24.6
.006	.240	30.7	32.1	29.5	32.0
.003	.122	21.9	26.4	25.5	26.3
.001	.059	19.4	24.1	23.7	24.1
.005	.207	25.2	30.2	28.3	30.1
.008	.284	32.3	34.7	31.4	34.7
.000	.021	18.0	22.9	22.8	22.9
.001	.041	19.5	23.5	23.2	23.5
.002	.083	17.6	24.9	24.3	24.9
.003	.155	22.0	27.8	26.5	27.7
.018	.466	56.3	52.3	42.7	53.3
.003	.138	21.5	27.1	26.0	27.0
.013	.387	47.6	43.0	36.9	43.3
.018	.466	57.8	52.3	42.7	53.3
.000	.011	22.8	22.6	22.5	22.6
.001	.071	17.4	24.5	24.0	24.5
.001	.049	15.9	23.8	23.4	23.7
.002	.099	20.7	25.5	24.8	25.5
.002	.114	22.0	26.1	25.2	26.0
.004	.183	23.6	29.1	27.4	29.0
.014	.415	45.7	46.0	38.8	46.4
.025	.535	62.2	63.7	49.3	66.1

P= 30.00
G= .15E+07

.000	.006	39.2	35.9	35.8	35.8
.000	.036	44.0	37.3	37.0	37.3
.001	.051	32.7	38.1	37.5	38.0
.002	.153	40.9	44.2	42.2	44.1
.003	.167	40.2	45.2	43.0	45.1
.001	.052	30.2	38.1	37.6	38.1
.000	.024	40.0	36.7	36.5	36.7
.000	.026	41.7	36.8	36.6	36.8
.002	.158	37.8	44.6	42.5	44.5
.000	.033	29.9	37.2	36.8	37.1
.001	.073	29.2	39.3	38.5	39.2
.002	.144	39.6	43.6	41.8	43.5
.001	.081	30.8	39.7	38.8	39.6

X QUALITY	ALPHA	ΔP EXP. (PSF)	ΔP MODEL A (PSF)	ΔP MODEL B (PSF)	ΔP MODEL D (PSF)
.002	.108	32.2	41.3	40.0	41.2
.002	.109	33.7	41.4	40.1	41.3
.003	.201	44.6	47.8	44.9	47.7
.001	.081	30.6	39.8	38.8	39.7

* * F E R R E L L S C O N T R A C T I O N D A T A * *

SYSTEM: STEAM/WATER

ORIENTATION: VERTICAL

X QUALITY	ΔP EXP. (PSF)	ΔP MODEL A (PSF)	ΔP MODEL B (PSF)	ΔP MODEL D (PSF)
--------------	-----------------------------	--------------------------------	--------------------------------	--------------------------------

SIG = .608
P = 117.
G = .400E+06

.0250	15.84	16.95	10.12	16.91
.0400	15.84	25.49	13.38	24.31
.0840	37.44	50.56	22.35	43.17
.1110	53.28	65.95	28.19	53.78
.1580	96.48	92.73	39.70	72.08
.0190	14.40	13.53	8.69	13.73
.2130	145.44	124.07	55.87	94.89
.2590	184.32	150.28	72.03	116.29
.3230	227.52	186.74	99.31	151.79

SIG = .608
P = 117.
G = .796E+06

.0120	37.44	37.82	28.26	38.39
.0270	57.60	71.70	45.22	69.64
.0380	86.40	96.54	56.51	90.99
.0680	161.28	164.30	86.59	145.60
.1060	250.56	250.13	127.78	213.99

SIG = .608
P = 117.
G = .994E+06

.0100	56.16	51.94	40.60	52.76
.1000	89.28	400.60	220.09	350.44
.0350	133.92	140.01	86.11	132.61
.0480	178.56	178.76	104.61	165.23
.0750	288.00	260.92	154.54	249.18

SIG = .608
P = 57.
G = .400E+06

.0740	57.60	85.69	33.00	66.62
-------	-------	-------	-------	-------

X QUALITY	ΔP EXP. (PSF)	ΔP MODEL A (PSF)	ΔP MODEL B (PSF)	ΔP MODEL D (PSF)
.1060	115.20	121.90	47.29	91.59
.1580	218.88	180.41	77.84	140.62
.2140	308.16	243.43	128.28	219.86
.0080	11.52	11.63	7.71	11.91
.0290	21.60	35.26	16.23	31.89

SIG = .608
P= 238.
G= .400E+06

.0110	7.20	5.94	4.94	6.00
.0350	11.52	12.77	8.51	13.04
.0750	18.72	24.15	13.42	23.26
.1110	27.36	34.39	17.69	31.51
.1670	46.08	50.32	24.83	43.39
.2280	69.12	67.68	33.75	55.90

SIG = .546
P= 116.
G= .731E+06

.0210	51.84	55.72	36.74	55.28
.0310	67.68	77.36	46.66	74.53
.0740	166.48	170.42	86.68	149.91
.1060	264.96	230.68	116.67	204.14
.1530	401.76	341.40	173.69	288.56
.0150	38.88	42.73	30.32	43.15
.0040	12.96	18.93	16.57	16.96
.2100	580.32	464.76	259.61	411.08

SIG = .546
P= 115.
G= .105E+07

.0370	319.68	357.83	230.43	337.77
.0230	214.56	237.83	165.35	231.80
.0110	112.32	134.96	106.02	136.15

SIG = .546
P= 56.
G= .731E+06

.0130	51.84	65.53	40.57	64.04
-------	-------	-------	-------	-------

Y QUALITY	ΔP EXP. (PSF)	ΔP MODEL A (PSF)	ΔP MODEL B (PSF)	ΔP MODEL D (PSF)
.0280	93.60	129.64	67.13	117.33
.0880	322.56	386.09	187.96	328.10

TABLE NO. 9.4

*** GEIGER'S CONTRACTION DATA ***

SYSTEM: STEAM/WATER

ORIENTATION: VERTICAL

R	X	AP	AP	AP	AP
MASS FLOW	QUALITY	EXP.	MODEL A	MODEL B	MODEL D
(LBM/SEC, HR)		(PSF)	(PSF)	(PSF)	(PSF)

SIG = .398

P = 200.

1.73	.012	180.0	179.7	151.0	182.5
1.51	.013	145.0	145.4	122.1	151.5
1.19	.019	107.0	114.0	88.4	116.8
.61	.027	66.0	71.0	49.7	71.6
.52	.042	41.0	40.7	24.0	40.7
1.21	.045	182.0	235.8	154.8	229.5
.07	.047	146.0	157.2	99.7	153.1
.63	.065	122.0	153.6	89.5	146.0
.78	.091	95.0	164.2	100.2	169.0
1.23	.052	203.0	276.2	176.7	265.9
.07	.068	183.0	218.2	129.0	206.2
.80	.079	150.0	187.6	105.4	174.9
.61	.110	97.0	133.5	67.7	120.2
.07	.085	236.0	265.5	151.2	245.9
.85	.099	218.0	253.2	126.9	212.6
.61	.138	150.0	166.8	82.7	145.9
.93	.105	283.0	295.0	162.0	267.7
.81	.123	236.0	258.6	136.2	230.5
.61	.158	190.0	187.8	92.5	161.8
.98	.086	267.0	270.8	156.5	254.2
.85	.114	243.0	269.0	144.2	241.9
.77	.104	221.0	202.8	107.9	183.9
.60	.148	131.0	167.5	82.5	145.8
.60	.211	231.0	241.3	120.2	202.2

SIG = .398

P = 300.

1.73	.021	214.0	200.7	165.5	208.2
1.50	.026	175.0	184.9	145.4	187.2
1.19	.034	106.0	130.3	100.8	135.6
.08	.048	123.0	118.5	82.4	119.3
.76	.055	55.0	78.5	51.9	78.3
.99	.076	35.0	63.0	38.0	61.8
1.17	.082	236.0	262.6	168.8	252.5

TABLE NO. 8.4 (CONTD...)

G	X	ΔP	ΔP	ΔP	ΔP
MASS FLOW	QUALITY	EXP.	MODEL A	MODEL B	MODEL D
(LBM/SGFT.HR)		(PSF)	(PSF)	(PSF)	(PSF)
.96	.099	205.0	216.4	132.1	205.4
.76	.131	145.0	168.6	95.4	156.1
.57	.175	126.0	125.4	66.4	112.0
.77	.173	210.0	221.8	122.8	199.6
.58	.233	140.0	167.0	88.7	140.8

SIG = .302

P = 400.

1.52	.004	81.0	71.4	69.5	71.3
1.19	.004	53.0	48.5	46.4	48.4
.98	.007	44.0	35.6	33.5	35.5
.80	.010	26.0	25.8	23.8	25.8
.60	.015	16.0	17.7	15.6	17.7
1.82	.023	206.0	201.2	175.4	203.5
1.53	.029	169.0	165.8	139.3	167.8
1.20	.037	109.0	118.9	95.4	120.0
1.02	.051	96.0	106.9	80.7	107.1
.80	.066	68.0	80.8	57.0	80.4
.60	.086	53.0	57.1	37.3	56.3
1.40	.076	235.0	274.8	199.4	269.3
1.21	.087	181.0	230.5	161.0	224.5
1.03	.102	153.0	191.0	128.3	185.3
.77	.135	122.0	138.5	85.5	131.3
.60	.171	98.0	104.3	60.6	97.0
1.13	.120	241.0	267.4	176.5	255.2
.95	.146	202.0	223.7	140.5	210.5
.76	.187	170.0	181.1	107.7	166.9
.59	.235	119.0	135.7	77.4	122.0

SIG = .253

P = 200.

2.37	.000	177.0	157.7	157.4	157.7
1.87	.000	107.0	99.9	99.5	99.9
1.55	.001	98.0	73.2	72.0	73.1
1.20	.002	70.0	49.3	47.4	49.2
.95	.005	61.0	41.4	37.3	41.5
2.45	.015	438.0	640.6	535.6	650.3
2.37	.021	450.0	570.3	450.6	574.9
1.82	.032	283.0	487.4	356.5	485.5
1.55	.042	286.0	410.7	282.5	404.8
1.20	.054	203.0	304.4	194.2	296.4
.91	.067	167.0	212.4	125.2	204.2

TABLE NO. 8.4 (CONTD...)

G MASS FLOW (LBM/SQFT.HR)	X QUALITY	ΔP EXP. (PSF)	ΔP MODEL A (PSF)	ΔP MODEL B (PSF)	ΔP MODEL C (PSF)
1.88	.074	741.0	995.7	652.7	952.1
1.55	.091	698.0	818.7	508.1	772.4
1.21	.107	596.0	578.9	337.0	538.0
.93	.155	444.0	487.8	265.1	440.0
1.88	.089	920.0	*82.5	766.0	*23.1
1.55	.111	700.0	988.6	608.7	926.4
1.21	.147	694.0	779.2	451.7	715.9
.93	.193	580.0	600.8	331.7	539.2

SIG = .253
P = 300.

2.35	.000	190.0	161.0	160.4	160.9
1.85	.002	117.0	110.6	108.3	110.4
1.52	.004	118.0	89.7	84.8	89.5
1.18	.010	86.0	71.2	63.3	71.3
.94	.009	52.0	43.8	39.1	43.9
2.71	.019	471.0	528.9	451.2	538.2
2.34	.025	402.0	473.4	387.9	480.0
1.84	.036	335.0	380.9	292.6	383.8
1.51	.049	267.0	324.7	234.2	324.1
1.18	.064	198.0	240.6	164.6	241.7
.92	.085	141.0	188.2	117.3	183.6
2.35	.063	742.0	953.5	695.8	937.5
1.85	.083	646.0	751.9	515.4	729.7
1.51	.098	448.0	578.2	377.2	555.7
1.18	.130	433.0	455.4	277.6	429.5
.92	.168	350.0	350.1	201.1	323.2
1.86	.103	802.0	911.4	612.1	875.4
1.52	.127	715.0	743.3	474.9	704.6
1.19	.165	516.0	580.8	350.5	540.3
.89	.222	441.0	427.6	245.2	387.4

SIG = .398
P = 500.

1.75	.005	121.0	97.7	94.3	97.5
1.48	.002	70.0	63.5	62.3	63.4
1.14	.008	48.0	45.8	43.2	45.7
.96	.010	38.0	35.0	32.4	34.9
.74	.015	8.0	20.3	21.7	24.4
.58	.017	7.0	15.6	13.7	15.7
1.76	.029	205.0	190.1	161.7	192.8
1.48	.036	147.0	153.4	126.2	156.2

TABLE NO. 8.4 (CONTD...)

G MASS FLOW (LBM/SECT, HR)	X QUALITY	Z P EXP. (PSF)	Z P MODEL A (PSF)	Z P MODEL B (PSF)	Z P MODEL D (PSF)
1.14	.040	100.0	103.0	81.6	105.0
.95	.053	77.0	80.8	61.6	82.2
.75	.071	38.0	62.3	44.4	63.1
.58	.095	23.0	46.7	30.9	46.8
1.08	.072	206.0	208.5	185.2	247.9
1.13	.096	172.0	183.0	127.6	180.5
.93	.115	128.0	144.1	96.0	141.1
.75	.140	97.0	111.2	70.1	107.5
.58	.188	57.0	83.7	49.8	79.3
1.17	.133	256.0	255.7	170.7	246.0
.93	.163	190.0	195.3	124.1	186.0
.74	.204	137.0	147.0	89.8	138.4
.57	.265	103.0	114.3	67.3	104.3

SIG = .253
P = 400.

2.67	.001	196.0	213.0	212.2	212.9
2.32	.001	180.0	169.2	167.3	169.1
1.83	.001	114.0	104.7	103.6	104.6
1.51	.000	87.0	67.3	67.2	67.3
1.20	.000	59.0	42.2	42.2	42.2
.91	.003	38.0	29.1	28.1	29.0
2.67	.019	425.0	439.3	384.3	443.2
2.32	.022	355.0	360.4	308.3	345.0
1.83	.037	255.0	310.3	243.4	317.0
1.50	.048	190.0	250.4	185.2	255.4
1.14	.064	148.0	181.2	123.7	184.4
.91	.082	98.0	142.0	89.9	144.0
2.66	.056	530.0	891.3	666.0	895.1
2.31	.047	725.0	749.7	551.2	769.6
1.81	.088	545.0	598.5	397.3	592.8
1.49	.107	425.0	474.2	297.0	466.1
1.09	.133	328.0	385.8	170.9	300.8
.91	.174	235.0	270.8	148.7	252.0
2.30	.088	900.0	961.1	653.7	947.9
1.80	.114	715.0	729.6	461.7	711.3
1.51	.135	578.0	598.0	360.5	577.5
1.20	.168	468.0	456.1	259.4	433.5
.91	.226	345.0	345.4	186.7	318.3

SIG = .253
P = 500.

2.60	.007	243.0	272.9	260.7	272.5
------	------	-------	-------	-------	-------

TABLE NO. 8.4 (CONTD...)

G MASS FLOW (LBM/SOFT.HP)	X QUALITY	ΔP EXP. (PSF)	ΔP MODEL A (PSF)	ΔP MODEL B (PSF)	ΔP MODEL D (PSF)
2.30	.005	200.0	192.6	186.1	192.3
1.82	.000	132.0	137.7	129.7	137.5
1.50	.005	113.0	80.7	77.9	80.6
1.17	.021	75.0	79.0	69.0	79.5
.90	.026	56.0	55.7	46.5	56.6
2.66	.030	478.0	504.4	434.7	512.1
2.32	.035	378.0	417.5	352.5	425.1
1.82	.040	279.0	283.0	232.2	288.2
1.50	.055	218.0	234.5	182.8	237.8
1.16	.071	168.0	171.2	125.8	172.8
.92	.095	140.0	134.3	92.4	138.4
2.65	.058	498.0	760.8	611.2	765.2
2.30	.068	524.0	651.2	507.3	652.1
1.82	.091	437.0	511.0	376.3	506.9
1.50	.113	375.0	414.8	291.4	407.8
1.16	.149	261.0	312.7	206.4	303.2
.90	.191	192.0	237.1	148.5	226.3
2.64	.084	832.0	*06.6	775.2	999.0
2.20	.098	860.0	856.4	639.8	845.4
1.82	.123	632.0	655.9	466.3	641.2
1.40	.152	476.0	524.2	356.3	507.0
1.18	.193	366.0	408.6	264.8	389.5
.93	.245	313.0	316.0	197.3	295.9

SIG = .144
P = 200.

4.82	.001	730.0	738.6	731.3	738.4
4.23	.000	620.0	536.3	535.3	536.2
3.30	.004	460.0	492.8	461.3	493.8
2.73	.006	440.0	386.0	352.1	388.0
2.10	.014	285.0	360.0	269.5	369.9
1.64	.023	231.0	308.6	236.3	315.8
2.78	.019	605.0	754.5	617.4	770.5
2.12	.040	600.0	791.9	573.5	794.7
1.67	.059	580.0	678.0	452.6	671.3
1.65	.086	850.0	930.3	596.4	907.3

SIG = .144
P = 300.

4.73	.000	800.0	680.3	680.1	680.4
4.18	.002	705.0	590.8	584.8	591.2
3.27	.006	605.0	468.0	448.6	469.4

TABLE NO. 8.4 (CONTD...)

G MASS FLOW (LBM/SHORT.HR)	X QUALITY	AP EXP. (PSF)	AP MODEL A (PSF)	AP MODEL B (PSF)	AP MODEL D (PSF)
2.69	.010	460.0	401.1	370.5	400.1
2.09	.019	330.0	329.2	286.9	336.0
1.67	.023	178.0	237.3	200.2	242.8
2.75	.025	740.0	694.8	594.8	707.9
2.09	.043	480.0	590.2	465.2	596.9
1.68	.046	475.0	537.7	390.9	537.8
1.70	.087	655.0	696.6	489.0	690.3
2.16	.052	636.0	725.6	561.0	730.5
2.79	.022	650.0	658.4	571.3	671.6

SIG = .144

P = 400.

4.73	.001	810.0	708.3	707.0	708.5
4.12	.002	735.0	587.1	581.0	587.5
3.23	.007	600.0	444.8	428.8	445.8
2.66	.011	456.0	361.1	338.6	362.9
2.06	.022	315.0	301.9	266.7	307.0
1.61	.027	216.0	208.6	178.4	213.7
2.71	.040	800.0	768.3	647.2	781.0
2.07	.059	560.0	591.6	447.2	592.0
1.61	.083	320.0	473.1	347.9	474.1
2.06	.100	970.0	910.2	675.3	904.7
1.61	.133	675.0	707.6	493.2	697.6
1.63	.155	924.0	837.1	578.2	821.3

SIG = .144

P = 500.

4.67	.000	820.0	696.3	694.6	696.3
4.04	.001	650.0	525.9	523.8	525.8
3.21	.005	510.0	397.7	385.3	397.6
2.62	.008	415.0	290.7	277.1	290.9
2.02	.021	218.0	249.7	222.1	252.1
1.56	.027	236.0	173.3	148.5	175.4
3.24	.026	852.0	727.6	642.9	738.5
2.65	.038	515.0	606.8	513.0	621.5
2.06	.054	525.0	463.2	371.0	473.3
1.57	.085	404.0	381.2	281.4	386.2
2.06	.103	806.0	766.4	567.6	768.6
1.60	.151	643.0	640.4	443.7	633.3
2.06	.122	990.0	823.2	643.4	850.3
1.60	.160	840.0	672.3	463.0	663.2

* * J A N S S E N ' S C O N T R A C T I O N D A T A * *

SYSTEM: STEAM/WATER

ORIENTATION: VERTICAL

G	X	ΔP	ΔP	ΔP	ΔP
MASS FLOW	QUALITY	EXP.	MODEL A	MODEL B	MODEL C
(LBM/SQFT.HR)		(PSF)	(PSF)	(PSF)	(PSF)

SIG = .492

P = 1000.

1.02	.204	151.8	135.9	99.7	135.7
1.03	.305	207.9	191.7	137.2	186.3
1.05	.370	246.0	230.6	165.9	220.5
1.02	.503	313.3	294.6	219.9	276.6
1.02	.608	365.8	349.2	273.6	325.9
1.03	.696	416.0	401.0	329.9	375.5
1.02	.812	458.1	456.0	401.9	434.2
1.02	.898	492.6	504.2	469.7	496.8
2.06	.095	312.6	314.8	262.3	320.1
2.06	.189	570.8	520.8	404.5	516.5
2.05	.289	787.7	728.5	553.1	707.2
2.05	.387	981.9	937.8	717.9	899.5
2.05	.480	1162.5	1131.2	887.8	1081.6
2.05	.570	1365.3	1324.9	1077.9	1273.1

*** FITZSIMMONS' CONTRACTION DATA ***

SYSTEM: STEAM/WATER

ORIENTATION: HORIZONTAL

X QUALITY	ΔP EXP. (PSF)	ΔP MODEL A (PSF)	ΔP MODEL B (PSF)	ΔP MODEL D (PSF)
--------------	-----------------------------	--------------------------------	--------------------------------	--------------------------------

SIG = .248
P = 1200.
G = .100E+07

.2075	2777.79	2677.62	2292.32	2280.94
.1810	2632.85	2416.64	2078.55	2064.54
.1205	1960.86	1820.82	1600.29	1568.64
.0900	1620.17	1520.45	1361.31	1315.62
.0605	1152.30	1229.93	1128.84	1058.58
.0305	882.67	934.48	888.10	799.38

SIG = .248
P = 1200.
G = .500E+06

.2280	792.51	731.58	590.37	610.95
.1775	664.62	605.23	494.92	509.82
.1135	407.95	445.09	370.93	379.30
.0866	363.57	377.79	330.35	323.06
.0555	299.27	299.97	271.90	253.74
.0255	220.90	224.91	213.45	189.06

SIG = .620
P = 1200.
G = .300E+07

.1625	1950.32	1910.31	1667.70	1666.03
.1200	1629.70	1552.48	1375.45	1363.17
.0800	1308.04	1215.69	1102.67	1074.62
.0400	921.57	878.91	827.42	771.14
.0180	728.02	693.67	672.45	607.27

SIG = .620
P = 1200.
G = .200E+07

.1800	934.36	910.80	769.04	794.08
-------	--------	--------	--------	--------

TABLE NO. 8.6 (CONTD...)

X QUALITY	ΔP EXP. (PSF)	ΔP MODEL A (PSF)	ΔP MODEL B (PSF)	ΔP MODEL D (PSF)
.1400	811.15	761.73	653.58	669.26
.0980	647.41	605.20	532.95	536.24
.0600	497.07	463.58	422.67	409.95
.0200	346.36	314.50	302.75	276.31

TABLE D-3

Expansion-Contraction Data

P = Pressure (psia)

G = Mass velocity ($\text{lbm}/\text{ft}^2\text{hr}$) based on small pipe

Model I - Homogeneous Model

Model J - Slip Flow

Model K - Slip Flow

Except at Vena Contracta where Mixing
Occurs

J A N S S E N S

EXPANSION-CONTRACTION DATA **

SYSTEM: STEAM/WATER

ORIENTATION: VERTICAL

G X $\Delta P_{TP}/\Delta P_{SP}$ $\Delta P_{TP}/\Delta P_{SP}$ $\Delta P_{TP}/\Delta P_{SP}$ $\Delta P_{TP}/\Delta P_{SP}$
 MASS FLOW QUALITY EXP. MODEL I MODEL J MODEL K
 (LBM/SGFT.HR)

SIG = .492

P = 1000.

1.02	.204	7.4	5.0	3.7	6.4
1.03	.305	10.0	7.0	5.1	8.7
1.03	.379	11.3	8.0	6.2	10.2
1.02	.503	13.7	10.9	8.2	12.0
1.02	.608	15.9	12.9	10.2	14.1
1.03	.696	17.3	14.7	12.2	15.5
1.02	.812	17.6	16.0	15.0	17.4
1.02	.898	19.0	18.6	17.5	19.5
2.06	.035	3.4	2.0	2.4	3.5
2.06	.189	6.7	4.7	3.7	5.8
2.05	.289	8.9	5.7	5.2	8.0
2.05	.387	11.0	8.6	6.3	10.1
2.05	.480	12.8	10.8	8.5	12.0
2.05	.570	14.2	12.2	10.2	13.8

EXPANSION-CONTRACTION DATA

FROM PRESENT INVESTIGATION

SYSTEM) FREQ-113/FREQ-113

ORIENTATION) HORIZONTAL

SG = 0.56

Y		$\Delta P_{TP}/\Delta P_{SP}$	$\Delta P_{TP}/\Delta P_{SP}$	$\Delta P_{TP}/\Delta P_{SP}$	$\Delta P_{TP}/\Delta P_{SP}$
QUALITY	ALPHA	EXP.	MODEL I	MODEL J	MODEL K

P= 30.00

G= .20E+07

.001	.061	1.01	1.10	1.08	1.12
.010	.412	3.32	2.08	1.78	2.53
.007	.341	2.61	1.77	1.58	2.05
.007	.320	2.40	1.70	1.52	1.99
.009	.382	3.02	1.90	1.60	2.30
.006	.301	2.54	1.63	1.48	1.84
.001	.053	1.07	1.08	1.07	1.10
.001	.080	.85	1.13	1.10	1.15
.002	.111	1.00	1.12	1.10	1.22
.002	.140	1.55	1.23	1.18	1.29
.004	.220	2.07	1.41	1.31	1.52
.008	.353	2.77	1.62	1.51	2.12
.007	.329	2.77	1.73	1.55	1.88
.009	.370	2.90	1.80	1.66	2.22
.009	.382	2.98	1.90	1.69	2.30
.009	.382	3.12	1.90	1.60	2.30
.010	.412	3.39	2.08	1.78	2.53
.000	.030	.96	1.05	1.04	1.06
.001	.052	.96	1.08	1.07	1.10
.001	.092	.98	1.15	1.12	1.12
.002	.122	.97	1.20	1.16	1.25
.003	.161	2.13	1.27	1.22	1.30
.003	.200	2.05	1.36	1.28	1.46
.005	.280	2.23	1.57	1.43	1.75
.008	.361	2.87	1.85	1.63	2.17
.013	.454	3.44	2.32	1.90	2.92

P= 40.00

G= .20E+07

.000	.023	.99	1.04	1.03	1.05
------	------	-----	------	------	------

Y QUALITY	ALPHA	EXP.	MODEL J	MODEL J	MODEL K
.004	.193	1.87	1.30	1.27	1.53
.005	.217	2.02	1.39	1.31	1.50
.006	.257	2.29	1.50	1.32	1.60
.007	.273	2.38	1.50	1.32	1.71
.008	.304	2.70	1.60	1.40	1.55
.012	.371	3.32	1.87	1.66	2.21
.014	.405	3.19	2.03	1.76	2.00
.002	.092	1.03	1.10	1.12	1.18
.003	.123	1.42	1.20	1.16	1.20
.000	.023	.99	1.02	1.03	1.05
.001	.061	1.10	1.10	1.08	1.11
.006	.209	2.13	1.47	1.37	1.61
.008	.289	2.40	1.59	1.45	1.77
.014	.405	3.32	2.03	1.76	2.40
.014	.405	3.00	2.03	1.76	2.40
.015	.422	3.55	2.12	1.81	2.57
.019	.473	3.90	2.41	2.01	3.08
.020	.491	4.42	2.53	2.09	3.29
.023	.517	4.17	2.70	2.22	3.61
.035	.600	5.67	3.61	2.70	4.93
.021	.500	3.71	2.40	2.13	3.40

R= 55.00

C= .20E+07

.000	.011	1.01	1.02	1.02	1.03
.000	.011	1.01	1.02	1.02	1.03
.001	.046	1.07	1.07	1.06	1.07
.002	.084	1.09	1.13	1.11	1.16
.003	.112	1.13	1.18	1.10	1.22
.005	.166	1.40	1.28	1.22	1.35
.006	.186	1.56	1.32	1.25	1.40
.006	.194	1.72	1.34	1.27	1.42
.001	.023	.92	1.00	1.03	1.05
.001	.031	1.01	1.05	1.00	1.06
.001	.054	1.15	1.08	1.07	1.10
.003	.098	1.12	1.15	1.12	1.18
.003	.108	1.18	1.17	1.14	1.21
.004	.139	1.25	1.23	1.18	1.28
.020	.423	3.57	2.10	1.81	2.55
.007	.210	1.78	1.37	1.29	1.47

X QUALITY	ALPHA	EXP.	MODEL I	MODEL J	MODEL K
.015	.364	2.85	1.84	1.63	2.14
.005	.146	1.61	1.22	1.22	1.35
.004	.123	1.34	1.20	1.16	1.24
.014	.339	2.72	1.75	1.56	2.00
.013	.323	2.17	1.49	1.52	1.91
.002	.069	.98	1.11	1.09	1.13
.006	.202	1.74	1.35	1.28	1.45
.015	.364	2.84	1.84	1.63	2.14
.020	.423	3.53	2.10	1.81	2.55
.023	.450	3.73	2.25	1.91	2.79
.027	.483	4.36	2.45	2.04	3.14

PM 75.00

GM .20E+07

.002	.061	1.20	1.09	1.08	1.11
.005	.123	1.18	1.20	1.16	1.24
.008	.186	1.83	1.32	1.25	1.40
.014	.274	2.36	1.53	1.41	1.60
.016	.299	2.34	1.60	1.46	1.70
.020	.348	2.37	1.77	1.58	2.03
.029	.432	3.52	2.13	1.83	2.59
.034	.466	3.87	2.32	1.96	2.90
.044	.519	3.96	2.68	2.20	3.40
.050	.547	3.80	2.91	2.34	3.82
.062	.593	5.48	3.38	2.60	4.52
.002	.054	1.13	1.08	1.07	1.10
.007	.171	1.75	1.28	1.23	1.35
.017	.315	2.61	1.65	1.50	1.84
.029	.432	3.60	2.13	1.83	2.59
.046	.528	4.14	2.75	2.24	3.60
.037	.484	3.65	2.43	2.03	3.00

PM 40.00

GM .25E+07

.000	.023	.98	1.08	1.03	1.05
.000	.023	.96	1.04	1.03	1.05
.001	.042	1.01	1.16	1.08	1.11
.002	.116	1.16	1.18	1.15	1.23

QUALITY	ALPHA	EXP.	MODEL I	MODEL J	MODEL K
.003	.124	1.23	1.20	1.16	1.20
.005	.211	1.30	1.38	1.30	1.87
.005	.219	1.55	1.39	1.31	1.50
.006	.259	1.83	1.50	1.39	1.60
.008	.291	1.97	1.50	1.46	1.77
.009	.329	2.08	1.69	1.53	1.92
.010	.301	2.27	1.75	1.57	2.00
.010	.301	2.02	1.75	1.57	2.00
.011	.370	2.52	1.86	1.65	2.17
.012	.382	2.47	1.92	1.69	2.25
.014	.408	2.49	2.03	1.77	2.83
.016	.442	2.91	2.21	1.89	2.71
.017	.459	3.14	2.31	1.95	2.87

P= 55.00

G= .25E+07

.007	.227	1.70	1.41	1.32	1.52
.002	.070	1.09	1.11	1.09	1.13
.007	.227	1.51	1.41	1.32	1.52
.009	.268	1.88	1.51	1.40	1.66
.013	.333	2.11	1.72	1.55	1.95
.017	.383	2.27	1.91	1.69	2.23
.004	.132	1.40	1.21	1.17	1.26
.001	.046	.90	1.07	1.06	1.09
.000	.015	.94	1.03	1.03	1.03
.001	.023	.94	1.04	1.03	1.05
.002	.070	1.09	1.11	1.09	1.13
.002	.085	1.13	1.13	1.11	1.16
.004	.124	1.21	1.20	1.16	1.20
.007	.219	1.55	1.39	1.31	1.49
.009	.260	1.82	1.49	1.39	1.63
.009	.260	1.88	1.49	1.39	1.63
.011	.300	2.19	1.61	1.47	1.79
.014	.350	2.39	1.75	1.59	2.03
.005	.164	1.48	1.27	1.22	1.34
.007	.219	1.63	1.39	1.31	1.49
.010	.276	2.03	1.54	1.42	1.69
.013	.333	2.28	1.72	1.55	1.95

P= 75.00

G= .20E+07

.020	.393	2.86	1.93	1.71	2.26
------	------	------	------	------	------

X QUALITY	ALPHA	EXP.	MODEL I	MODEL J	MODEL K
.026	.410	2.89	2.01	1.76	2.38
.016	.301	1.99	1.60	1.57	1.79
.017	.317	2.14	1.65	1.51	1.86
.001	.015	1.08	1.03	1.03	1.03
.002	.012	1.00	1.09	1.08	1.11
.008	.180	1.61	1.30	1.20	1.37
.013	.268	1.79	1.51	1.40	1.65
.021	.352	2.08	1.80	1.61	2.06
.027	.418	2.20	2.05	1.79	2.40
.037	.488	3.24	2.43	2.05	3.06
.042	.510	3.56	2.61	2.17	3.35
.049	.546	3.67	2.87	2.34	3.72

EXPANSION-CONTRACTION DATA
FROM PRESENT INVESTIGATION
SYSTEM: FREON-113/FREON-113
ORIENTATION: HORIZONTAL

SIG = 0.25

Y QUALITY	ALPHA	$\Delta P_{TP}/\Delta P_{SP}$ EXP.	$\Delta P_{TP}/\Delta P_{SP}$ MODEL I	$\Delta P_{TP}/\Delta P_{SP}$ MODEL J	$\Delta P_{TP}/\Delta P_{SP}$ MODEL K
--------------	-------	---------------------------------------	--	--	--

P = 65.00
G = .16E+07

.001	.017	1.00	1.02	1.02	1.02
.002	.059	1.25	1.08	1.06	1.09
.009	.224	1.65	1.38	1.30	1.42
.015	.331	2.11	1.68	1.51	1.76
.021	.399	2.40	1.94	1.69	2.07
.010	.250	1.78	1.45	1.34	1.49
.003	.165	1.34	1.15	1.12	1.16
.001	.030	1.09	1.04	1.03	1.04
.003	.098	1.31	1.14	1.11	1.15
.002	.059	1.25	1.08	1.06	1.09
.004	.113	1.35	1.17	1.13	1.18
.001	.040	1.32	1.05	1.04	1.06
.005	.146	1.48	1.22	1.18	1.24
.014	.314	2.01	1.63	1.47	1.70
.020	.433	2.65	2.10	1.80	2.27
.003	.556	3.44	2.92	2.33	3.33

P = 65.00
G = .11E+07

.003	.107	1.10	1.16	1.12	1.17
.009	.229	1.47	1.40	1.31	1.40
.004	.132	1.10	1.20	1.16	1.22
.007	.196	1.23	1.33	1.25	1.36
.001	.043	1.00	1.06	1.05	1.06
.002	.058	1.00	1.08	1.06	1.09
.005	.147	1.09	1.23	1.18	1.25
.025	.432	2.09	2.12	1.79	2.31
.005	.135	1.10	1.21	1.16	1.22
.002	.049	1.00	1.07	1.05	1.07
.006	.174	1.15	1.28	1.22	1.31
.003	.088	.98	1.13	1.10	1.13

Y QUALITY	ALPHA	EXP.	MODEL T	MODEL J	MODEL K
.018	.361	1.70	1.80	1.59	1.02
.025	.432	2.23	2.12	1.70	2.31
.035	.505	2.79	2.57	2.08	2.90
.056	.605	3.63	3.53	2.65	4.10
.069	.644	4.20	4.09	2.96	4.76
.050	.580	3.03	3.20	2.48	3.75
.040	.534	2.91	2.79	2.21	3.20
.034	.499	2.61	2.52	2.05	2.84
.007	.196	1.21	1.33	1.25	1.36

P= 40.00
G= .16E+07

.000	.008	1.00	1.01	1.01	1.01
.000	.017	1.00	1.02	1.02	1.02
.001	.052	1.26	1.07	1.06	1.08
.002	.106	1.40	1.16	1.12	1.17
.003	.144	1.45	1.22	1.18	1.20
.004	.175	1.47	1.28	1.22	1.31
.004	.182	1.36	1.30	1.23	1.32
.006	.238	1.59	1.42	1.33	1.47
.000	.022	1.05	1.03	1.02	1.03
.001	.074	1.20	1.10	1.08	1.11
.003	.157	1.21	1.25	1.19	1.27
.003	.106	1.25	1.16	1.12	1.17
.003	.156	1.26	1.25	1.19	1.27
.006	.235	1.48	1.42	1.32	1.46
.000	.011	1.10	1.01	1.01	1.02
.001	.039	1.17	1.05	1.04	1.06
.000	.017	1.10	1.02	1.02	1.02
.001	.039	.98	1.05	1.04	1.06
.001	.039	.98	1.05	1.04	1.06
.001	.072	1.10	1.10	1.08	1.11
.002	.109	1.15	1.16	1.13	1.17
.000	.175	1.16	1.28	1.22	1.31
.008	.287	1.32	1.56	1.42	1.62
.002	.109	1.42	1.16	1.13	1.17
.001	.028	1.00	1.04	1.03	1.04
.001	.063	1.23	1.09	1.07	1.09
.000	.010	.81	1.01	1.01	1.01
.001	.074	1.27	1.10	1.08	1.11

P= 40.00
G= .11E+07

.002	.118	1.11	1.18	1.14	1.19
------	------	------	------	------	------

X QUALITY	ALPHA	EXP.	MODEL I	MODEL J	MODEL K
.000	.025	1.10	1.03	1.03	1.04
.006	.245	1.51	1.05	1.34	1.50
.015	.433	2.17	2.15	1.81	2.36
.001	.076	1.16	1.11	1.09	1.12
.004	.240	1.49	1.44	1.33	1.49
.003	.122	1.16	1.10	1.14	1.20
.001	.059	1.05	1.08	1.06	1.09
.005	.207	1.21	1.36	1.27	1.39
.008	.284	1.46	1.56	1.41	1.62
.000	.021	.98	1.03	1.02	1.03
.001	.041	1.06	1.06	1.04	1.06
.002	.083	1.08	1.12	1.09	1.13
.003	.155	1.11	1.25	1.19	1.27
.018	.466	2.50	2.35	1.93	2.61
.003	.138	1.20	1.22	1.17	1.23
.013	.387	2.22	1.93	1.67	2.07
.018	.466	2.51	2.35	1.93	2.61
.000	.011	.99	1.01	1.01	1.02
.001	.071	.92	1.10	1.08	1.11
.001	.049	.93	1.07	1.05	1.07
.002	.099	1.03	1.15	1.11	1.16
.002	.114	1.01	1.17	1.13	1.18
.004	.183	1.14	1.31	1.23	1.33
.014	.415	2.18	2.06	1.75	2.24
.025	.535	2.88	2.86	2.24	3.31

P= 30.00
G= .15E+07

.000	.006	1.00	1.01	1.01	1.01
.000	.036	1.08	1.05	1.04	1.05
.001	.051	1.44	1.07	1.06	1.07
.002	.153	1.46	1.24	1.19	1.26
.003	.167	1.46	1.27	1.21	1.29
.001	.052	1.00	1.07	1.06	1.08
.000	.024	1.07	1.03	1.03	1.03
.000	.026	1.13	1.03	1.03	1.04
.002	.158	1.28	1.25	1.20	1.27
.000	.033	1.12	1.04	1.04	1.05
.001	.073	1.33	1.10	1.08	1.11
.002	.144	1.56	1.23	1.18	1.24
.001	.081	1.33	1.12	1.09	1.12

Y QUALITY	ALPHA	EXP.	MODEL J	MODEL J	MODEL K
.002	.108	1.38	1.16	1.13	1.17
.002	.109	1.40	1.16	1.13	1.18
.003	.201	1.63	1.34	1.26	1.38
.001	.081	1.33	1.12	1.09	1.13
RM CV					