COO-2152-13

University of Cincinnati

Department of Chemical and Nuclear Engineering

Quarterly Progress Report

Period Ending September 30, 1974

MASTER

Investigation of Pressure Drops
and Heat Transfer Coefficients
for Loss of Coolant Evaluations

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Report COO-21512-13

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Contract AT(11-1)2152

"Investigation of Pressure Drops and
Heat Transfer Coefficients for Loss
of Coolant Evaluation"

Quarterly Report for Period July, 1974
to September 30, 1974

This contract has as its objective the study of pressure drop and heat transfer phenomena of importance during the loss of coolant accident. The study is divided into three experiments

- a) Transient Pressure Drop Investigation
- b) Two-Phase Pressure Drop and Flow Pattern Study
- c) Transition Boiling and Reflooding Heat transfer Tests

I. Transient Pressure Drop Investigation

The transient pressure drop apparatus is operated by discharging heated Freon 113 from a large storage accumulator to the test liners. The Freon flashes across a needle valve and then proceeds to a three-way valve. There a portion of the two-phase mixture is directed through a storage accumulator and the remainder directed to the test section. By appropriately varying the position of the 3-way valve, a sinusoidally varying flow is obtained.

The early data gathered in this program were obtained without a direct void fraction measurement. Void fractions were estimated by comparing volumetric flow rates from the turbine meter to total mass flow rates from a weigh cell on the receiving accumulator. It was previously reported that these estimates were in poor agreement with actual void fraction measurements made with U.C's. capacitance type voidmeter. A correlation was found between the measured and estimated

voids and this correlation was used to recalculate the early data. The results of this recalculation, reported in the previous quarterly report [C00-2152-12] indicated an improved agreement between observed and calculated results. Nevertheless, the observed results for the expansion-contraction combination showed significant discrepancies with the calculations.

In this quarter, a revised set of data were obtained. Void fraction measurements were obtained with each run. The data which are compared to calculations are the phase shift between the Δp and flow curves and the ratio of head to flow fluctuations. Care was taken to operate under conditions such that the phase shift between flow and Δp was nearly the same when measured from shifts in the peaks or the minimums. In the earlier data, differences were observed between these shifts and an average value was reported.

Additional runs with a straight pipe test section were also made. From these runs, revised estimates of the sonic velocity were obtained.

Figs. 1 and 2 compare the observed phase shifts with those calculated by the method of impedance.⁽¹⁾ In using the impedance procedure, it is necessary to assume homogeneous flow. Calculations were made assuming the fluid to behave as if the average density, ρ_{av} , was simply $(1-\alpha)\rho_l$. This ignores the momentum flux due to the vapor but this quantity is negligible at the low gas densities of the present experiment.

Figs. 1 and 2 show generally good agreement between observed and calculated values. There is no longer a major discrepancy between the calculated and observed results for the expansion-contraction combination. The calculated phase shift is somewhat low at void fractions above 50%.

This would indicate that the pressure loss coefficient being used is somewhat high in that region. A similar trend is shown by the to flow fluctuation ratio (Fig. 3 and 4) at high voids. The results do show the general agreement of one dimensional momentum theory with observations.

A new test section is now being installed in the test apparatus. This section contains a 1/2 in. thick plate in which a single hole has been drilled. Oscillatory flow experiments across this restriction are scheduled for the next quarter.

II. Two Phase Pressure Drop and Flow Pattern Study

Summary of Previous Results

A report summarizing the results of the investigations which have been carried out to date is now in preparation. A summary of the conclusions of this report is presented here for ready reference.

Since flow pattern and pressure drop are strongly connected, a study was made of the transition from homogeneous to non-homogeneous flow. Fig. 5 shows the data from the present study, and the literature plotted on a modified Baker plot. It is seen that the transition is well correlated by the very simple equation

$$G_T = 2 \times 10^6 \text{ lbs/hr ft}^2 \quad (1)$$

where G_T = total mass velocity.

A theoretical analysis of the froth flow region has been developed and the above working correlation is shown to be an approximation of the analytical result.

The steady state pressure drop across abrupt area changes have been measured in a circulating Freon loop. The data obtained, as well as the steam water data in the literature, have been analyzed. The analysis has followed the one dimensional momentum balance approach used by Janssen.⁽²⁾

For the steady state, total pressure change across abrupt expansion, Janssen⁽²⁾ obtained

$$\Delta P_{\text{expansion}} = \frac{G^2}{\rho_l g_c} \left\{ \left(\frac{\rho_l}{\rho_g} \right) x^2 \left[\frac{1}{\alpha_1 \sigma} - \frac{1}{\alpha_2} \right] + (1-x)^2 \left[\frac{1}{\sigma(1-\alpha_1)} - \frac{1}{(1-\alpha_2)} \right] \right\} \quad (2)$$

where α_1, α_2 = void fractions upstream and downstream, respectively, of expansion

σ = area ratio

G = total mass flow

ρ_l, ρ_g = liquid and vapor densities, respectively

x = mixture quality

Use of this equation requires a knowledge of the appropriate value of α_1 and α_2 . The literature data (Note: No direct measurements across expansions were made in current tests. Current tests covered contractions and expansion-contraction combinations) were best correlated when α_1 and α_2 were taken as the α 's to be expected in straight pipe of the appropriate size under the given flow conditions. Hughmark's⁽³⁾ void fraction correlation was used for

the estimation. A comparison of calculated and observed results are given in Fig. 6*.

A statistical analysis compared the above slip flow model to a homogeneous model (α_1 and α_2 estimated assuming zero slip). For low flows, the homogeneous model was a very poor fit of the data, as the mass velocity increased, the ability of the homogeneous model to predict the data improved. For $G > 2 \times 10^6$ the homogeneous model predicted the data about as well as the slip model. This would seem to provide further confirmation for the postulate that the two-phase flow may be considered as homogeneous if $G > 2 \times 10^6$ lbs/hr ft².

The literature data, and present experimental data, for pressure drop across contractions were examined. A one dimensional momentum balance yields⁽²⁾ for the pressure loss across a contraction.

$$\begin{aligned} \Delta P_{\text{contraction}} = G^2 / \bar{\rho}_L \cdot 2g_c \left[\frac{1}{\sigma^2} \left\{ R x^2 \bar{\alpha}_1 (1/C^2 \alpha_3^2 - 1/\alpha_2^2) + (1-x)^2 (1-\bar{\alpha}_1) \right. \right. \\ \left. \left(1/C^2 (1-\alpha_3)^2 - 1/(1-\alpha_2)^2 \right) - 2/\sigma^2 \left(R x^2 (1/C \alpha_3 - 1/\alpha_2) \right. \right. \\ \left. \left. + (1-x)^2 \left(1/C (1-\alpha_3) \right) - 1/(1-\alpha_2) \right) \right. \\ \left. + R x^2 \bar{\alpha}_2 \left(1/\sigma^2 \alpha_2^2 - 1/\alpha_1^2 \right) \right. \\ \left. \left. + (1-x)^2 (1-\bar{\alpha}_2) \left\{ 1/\sigma^2 (1-\alpha_2) - 1/(1-\alpha_1)^2 \right\} \right] \right] \quad (3) \end{aligned}$$

*A similar fig. was shown as the Quarterly Progress Report for the Period Ending December 30, 1973. (C00-2152-10). In that report the lower dashed line was mislabeled.

where R = ratio of liquid to vapor density

C = vena contracta area ratio

α_1, α_2 = void fractions upstream and downstream of contraction

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

$$\bar{\alpha}_2 = (\alpha_1 + \alpha_2)/2$$

α_3 = void fraction at vena contracta

It was assumed that the value of C for two-phase flow was the same as for single phase flow.

The contraction data could be well correlated by again assuming that α_1 and α_2 were these which would exist in a straight pipe at the corresponding conditions. When experimental α values were not available, estimates of α were again obtained using Hughmark's correlation.⁽³⁾ The value of the void fraction α_3 at the vena contraction was taken as more closely approaching the homogeneous value. By taking

$$\alpha_3 = \alpha_2 (\alpha_{\text{homog}} - \alpha_2)^k \quad (4)$$

where $k = 1$ if $\alpha_2 < .6$

$$k = 1 - 1.25 (\alpha_2 - .6) \text{ for } \alpha_2 > .6$$

a good correlation (see Fig. 7) was obtained.

It was also found, however, that the data could be correlated about as well by assuming that $\alpha_1 = \alpha_2 = \alpha_3 = \alpha_{\text{homogeneous}}$ (when no significant vaporization occurred). While this is not in accord with experimentally observed α 's upstream and downstream, it is a convenient approach for design purposes.

The total pressure drop, ΔP_2 across an expansion-contraction combination may be computed by

$$\Delta P_2 = \Delta P_{\text{contraction}} - \Delta P_{\text{expansion}}$$

The present data plus those of Janssen et al⁽²⁾ for such combinations are compared to the sum of Equations (2) and (3) in Fig. 8. The model is in good agreement with the data. Note that it is not appropriate to represent these results by a simple K value.

Current Experimental Work

The data and analyses reported above all apply to expansions and contractions which are significantly separated. Some of the data in the literature indicate that, as the contraction and expansion are brought close together, the mixing at the vena contracta may be less complete. During this quarter, data was obtained with a test section having a $\sigma = 0.62$, small pipe diameter = 0.78 in., and a 2 in. length between the area changes. Typical data across the expansion-contraction combination are shown in Fig. 9. It may be seen that, for the 2 inch separation, there is no significant difference between these data, and those previously obtained (appropriately corrected for pipe friction) with an 18 inch length between the area changes.

III. Transition Boiling and Reflood Heat Transfer Tests

These experiments are being conducted in order to measure transition boiling heat transfer coefficients under conditions somewhat similar to those encountered during the reflood phase of a LOCA. To obtain the desired data, mercury is circulated through a steel loop by means of a canned motor pump.

In the test section, mercury flows downward on the inside of a 1/4 in. (nominal IPS) pipe. Water flows upward in an annular around the pipe containing the mercury. Since the outer pipe is glass, visual observations of the boiling process are possible.

A series of thermocouples, spaced approximately every 4 inches, are placed inside the mercury. By reading the temperature difference between adjacent thermocouple and measuring the total mercury flow, the average heat flux over the four inch section may be obtained. Heat transfer coefficients are then computed by calculating an outer wall temperature, T_w , and division of the flux by $(T_w - T_{sat})$.

Data have now been obtained over a range of flow rates from 1.2×10^4 to 3.4×10^4 lbs/hr ft². The raw data obtained are shown in Figs. 9 through 12. The data at the lowest flow rates were obtained by fixing the flow and steadily increasing temperature. Data at the higher flows were obtained by proceeding well into the transition boiling region (high Δt_{sat}) increasing the flow and then decreasing the mercury temperature. The high and low flow results appear to be consistent.

Each symbol on Figs. 10-13 represents the results of a different thermocouple. The offset between the results from different thermocouples is believed due to:

- (a) differing steam qualities at different axial locations
- (b) some thermocouples having taken on radial positions closer to the wall than assumed in the calculations

The latter effect is being examined prior to calculations of heat transfer coefficients. To do so, the non-boiling data, which should not vary with axial location, is being studied to determine what corrections should be made to the present calculations.

References

- (1) Streeter, V. L. and E. B. Wylie, "Hydraulic Transients", p 20, McGraw Hill, New York (1967).
- (2) Janssen, E., "Two-Phase Pressure Loss Across Abrupt Contractions and Expansions Steam Water at 600 to 1400 psia", Int. Heat Transfer Conf., Vol. 5, p 13 ASME (1966).
- (3) Hughmark, G. A., AIChE J. 19, 1062 (1973).

Fig 1 - Comparison of Observed and
Predicted Phase Shifts
(contraction)

Fig 2 Comparison of Observed and Predicted
Phase Shifts (Contraction + Expansion)

Fig 3
Comparison
of Observed
and Predicted
Head-to-Flow
Fluctuation
Ratios
(Contraction)

Fig 4
Comparison of
Observed and
Predicted
Head-to-Flow
Fluctuation
Ratios
(Contr. + Exp.)

Fig 5

Modified Baker Plot for Non-Homogeneous-Homogeneous Transition

Fig 6

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

Fig 7

Legend

- Farral & McGee
- Janssen
- * Geiger
- △ Present Investigation

Comparison of Pressure Drop Across Abrupt Contraction With Model

Fig 8

Legend

△ Janssen (Steam Water)

Present Investigation (Freon 113)

● $\sigma = 0.5$

* $\sigma = 0.25$

Comparison of Contraction ΔP With Model For
Expansion-Contraction Combination

Fig 9 - Effect of Distance Between Expansion & Contraction

Fig 10 - Raw Transition Boiling Data

Fig 11 Raw Transition Boiling Data

q''_{WL} VS. ΔT_{SAT}

$$G_W = 1.365 \times 10^4 \text{ Lbm/hr.ft}^2$$

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SEMI-COORDINATE SYSTEMS
 q''_{WL} (BTU/hr.ft²)
 ΔT_{SAT} (°F)

Fig 12 Raw Transition Boiling Data

q''_{WL} Vs. ΔT_{SAT}

$$G_W = 2.0475 \times 10^4 \text{ Lbm/hr.ft}^2$$

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SEMI-LOG PLOT
KEUFFEL & ESSER CO.
CYCLES IN INCHES
10 DIVISIONS

Fig 13 Row Transition Boiling Data

q''_{WL} Vs. ΔT_{SAT}

$G_W = 3.444 \times 10^4 \text{ lbm/hr.ft}^2$

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SEMI-LOG SCALE
CYCLES TO DIVISIONS
↑
 $q''_{WL} (\text{BTU/hr.ft}^2)$

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