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

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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 1 to Sept. 30, 1973

The objective of this contract is the study of pressure drop and heat transfer phenomena of importance during a 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 operates by discharging heated Freon 113 from a large storage accumulator to the test lines. The Freon flashes across a needle valve and a 3-way valve directs a portion of the 2 phase mixture to a storage accumulator and the remainder through the test section. By appropriately varying the position of the 3-way valve, a sinusoidally varying flow is obtained.

During the previous quarter, conditions were established under which transient two-phase pressure drop data could be obtained. Preliminary analyses of these data assuming incompressible flow were not capable of explaining the results obtained. During this quarter, a substantial amount of additional two-phase data were obtained. These data indicated that the sonic velocity dropped rapidly with void fraction and appropriate consideration of this fact was required.

Analysis of the system behavior considering sonic velocity effects can be accomplished by use of the hydraulic impedance method⁽¹⁾. The method allows the prediction of the phase shift between the flow and pressure drop curves. To obtain the sonic velocity required for this prediction, tests were made using a straight pipe test section. After verifying by steady state tests that the expected friction factors were obtained, a series of transient tests were conducted. The observed phase shifts were then used to determine sonic velocities.

Transient pressure drop data were then obtained with two abrupt area change test sections. The first of these, TS#1, had an area ratio of 0.09 while the second, TS#2, had an area ratio of 0.35. Pressure drop data were obtained across the contraction and the expansion-contraction combination. The expansion-contraction combination was chosen rather than the expansion because in previous tests difficulty had been encountered with the low Δp across the expansion alone. Figures 1 and 2 are plots of average phase shift between flow and Δp vs. void fraction for the contraction and expansion-contraction combination of TS#1. Data was taken at two cycle rates as shown in the graphs. Meaningful data at lower cycle rates could not be obtained. Also shown in Figures 1 and 2 are theoretical curves of average shift vs. void fraction for both cycle rates using the impedance method and three different sets of overall loss coefficients. The set consisting of $K_{CT} = 2.21$ and $K_{ST} = 2.61$ are the results of steady-state runs. Although there is considerable scatter in the data, the curves seem to provide a reasonable prediction of the contraction data. The contraction-expansion data would appear to indicate a somewhat higher loss coefficient was required to correlate the data.

The data obtained for TS#2 are compared with calculations obtained using 3 loss coefficients in Fig. 3 and 4. The loss coefficients obtained from steady state data are: $K_{CT} = 2.00$ and $K_{ST} = 2.03$. The scatter in this data is much less than observed for TS#1 and it is clear that quite reasonable agreement is obtained for the contraction. It is also clear that the contraction-expansion would require higher use of higher loss coefficients to obtain agreement.

The data obtained to date indicate that one-dimensional momentum theory, coupled with the assumption of homogeneous flow, may be used for prediction of transient Δp across contractions. The data obtained across the expansion-contraction combination are not well explained and further investigation is required.

II. Two-Phase Pressure Drop and Flow Pattern Study

Experimental Work. These experiments are being conducted in a recirculating loop using Freon-113. Two phase pressure drops across abrupt area changes are being determined. Additional data has been obtained with the glass test section previously described. In addition, photographs of flow patterns at the area changes have been obtained. Steady state pressure drop data across two other test sections have been obtained using the transient pressure drop apparatus.

An extensive study of the pressure drop data has been undertaken. The earlier conclusion that significant flashing occurred in the glass test section appears to be in error. The most consistent analyses results when it is assumed that essentially no flashing occurred across the test test section. To verify this conclusion a second void detector

has been built. After calibration, it will be installed in the loop and void measurements before and after the test section will be possible.

A review of the data from the previous test section (see report COO-2152-6) indicated that the dip in the loss coefficients at low void fraction was largely spurious. The dip appears largely the result of an overestimation of friction losses in this region.

Analysis of Contraction Data. The contraction Δp from this study, as well as the available literature data, have been extensively reviewed. It has been concluded that, rather than analyze the data in terms of loss coefficients, it is more fruitful to consider the data in terms of the ratio of two phase pressure drop to single phase pressure drop. One may then readily compare the data obtained to the various models proposed.

By applying a force-momentum balance and assuming that no losses occur from section 1 to section 3, Janssen⁽²⁾ derived the following expression for the two-phase pressure drop across an abrupt contraction.

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

where;

G_1 is total mass velocity at section 1; lbm/ft²-hr.

v_f is specific volume of liquid phase, ft³/lbm.

R is ratio of liquid density to vapor density.

C is vena contracta area ratio

σ is channel area ratio

X is the mixture quality

α_i is the void fraction at i th section

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

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

g_c is the gravitational convection factor.

Subscripts

1 = upstream of contraction

2 = at area change

3 = at vena contracta

4 = downstream of contraction

If the values of α_s and C are available, pressure drops across an abrupt contraction can be calculated.

Janssen⁽²⁾ assumed that (a) $C_{sp}/C_{TP} = 1$; (b) α_s could be obtained by use of one of the three models listed below.

Model #1. No slip exists between the phases.

Model #2. Slip exists and can be calculated using the relations available for slip in straight sections.

Model #3. No slip at the vena contracta but at other sections it exists as in Model #2.

In addition, one may propose

Model #4. Slip upstream but no slip at the vena contracta or downstream.

In the low to moderate quality region (region in which data of this investigation were obtained), Models #1 and #3 predict essentially the same values. At high quality, model #3 predicts higher pressure drop values. Model #4 predicts the highest pressure drops.

Figs. 5, 6 and 7 compare the measured pressure drop from this investigation to Model #1 (labelled homogenous in figures) and Model #2 (labelled separated on figures). The scatter of the data makes it difficult to come to a firm conclusion. At values of α below about 40%, there seem to be some tendency for the data to follow the separated model line. For $\alpha > 40\%$, the homogeneous model (Model #1) would seem to be a somewhat better fit. There also seems to be some indication that the data at high area ratios (high σ) follow the homogeneous prediction more closely.

Figs. 8 and 9 further examine the possibility of α and σ trends. In Fig. 8, all available data for the low to moderate α range are compared to the homogeneous model. When all of the data is considered, no clear deviation emerges. Fig. 9 compares data for high and low σ with the homogeneous model, again no clear trend emerges.

Finally, all of the available data (2)(3)(4) are compared with Models #1, #2 and #3 in Fig. 10, 11 and 12. It appears fairly clear that the homogeneous model (Model #1) gives the best overall agreement with world data. Model #2 in general underpredicts the observed pressure drops while Model #3 overpredicts the pressure drops. Since Model #4 predicts higher pressure drop values than #3, it is not shown.

III. Transition Boiling and Reflooding Heat Transfer Tests

Experimental. These experiments are being conducted in a heat transfer loop using hot mercury as the heat source. Boiling of water tubes place in a vertical glass annulus around the pipe.

Further apparatus difficulties have delayed testing during this quarter. The earlier difficulties with the sliding seal on the water side has been surmounted by replacing the seal with a bellows joint. After a short period of satisfactory loop operation, difficulty developed with the flow indication system. The cause of the difficulty is now being investigated.

Theoretical. The previously reported transition boiling correlation has been slightly modified. The basic assumptions that the transition boiling h has a convective and a boiling component was retained, but the boiling component has been revised to :

$$h_b = (0.5) S \cdot h_m \{ \exp[-0.0078(\Delta T - \Delta T_m)] + \exp[-0.0698(\Delta T - \Delta T_m)] \} \quad (2)$$

The total heat transfer coefficient is given by

$$h_T = h_b + h_c \quad (3)$$

where h_c is the convective component.

All other terms have been defined in a previous report (No. C00-2182-7). The revision was based on more data available from Nobel⁽⁹⁾. The correlation fit for the boiling component is shown in Fig. 13. The overall transition boiling correlation is compared with data in Fig. 14. Better

than 75% of the data lie within 30% of the prediction. The prediction is also compared with that of McDonough et al⁽⁵⁾:

$$(\phi_{B.O} - \phi_Z)/(T_W - T_{DNB}) = 730 \exp[576/P] \quad (4)$$

It should be noted that with the exception of a single point the original data of McDonough et al. are no longer available. Hence the comparison in Fig. 14 is based on typical condition cited for this single data point. The only inference that is drawn is that there is no major disagreement between this data and those of the other investigators.

A comparison of the revised correlations with the FLECHT⁽¹¹⁾ data is shown in Fig. 15 for a range of qualities for two typical data sets. A direct comparison is not possible since that FLECHT data do not yield any values for the quality.

An attempt has been made at the prediction of rewetting conditions. Rewetting is assumed to occur when the boiling component is comparable to the convective component. We can then define rewetting to occur when the following conditions is satisfied:

$$h_c = 0.5 S h_m [\exp[-0.078(\Delta T_{REWET} - \Delta T_m)] + \exp[-0.0698(\Delta T_{REWET} - \Delta T_m)]] \quad (5)$$

In Fig. 16, ΔT_{REWET} has been computed using the above equations for several FLECHT points, again for a range of qualities. It can be seen that the data seems to fall within the predicted band.

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FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 4

Figure 5 :Ratio of Two-Phase to Single-Phase Pressure Drop
across a sudden contraction of Area Ratio 0.5

Present Investigation

P, PSIG

G, lbm/Ft²-Sec

50	1.6×10^6
50	1.1×10^6
25	1.6×10^6
25	1.1×10^6

4.0

Homogeneous
Model

3.0

Seperated Model

2.0

1.0

Figure: 6 : Ratio of Two-Phase to Single-Phase Pressure Drop
across a sudden Contraction of Area Ratio 0.25

Fig. 3 Comparison of Homogeneous Flow Model Predictions with existing Data at low Void Fraction values ($\alpha = 0 \rightarrow 40$)

LOGARITHMIC
SCALE
3 CYCLES

Figure : 9 : Comparison of Homogeneous Flow Model Predictions with Existing Data for $\sigma > .5$ & $\sigma < .25$

LOGARITHMIC
 359-1206
 K. E. NEUFFEL & SONS CO. BOSTON, U.S.A.
 3 X 5 CYCLES

Figure:10: Comparison of Homogeneous Flow Model Predictions with the available Data.

LOGARITHMIC 350-120G
 LEUPOLD & RUDER CO. MILWAUKEE, WIS.
 3 X 3 CYCLES

Figure : 11 : Comparison of Model # 2 Predictions with the available Data.

LOGARITHMIC 350-120G
KEUFFEL & ESSER CO. MADE IN U.S.A.
3 X 3 CYCLES

Figure : 12 : Comparison of Model #3 Predictions with the available Data.

FIG 13. BOILING COMPONENT OF
FLOW BOILING DATA

FIG. 14. COMPARISON OF PREDICTION WITH DATA
AND WITH EQN. (4).

FIG.15. COMPARISON OF PREDICTION
WITH FLECHT DATA

FIG.16. PREDICTION OF REWETTING
POINTS FOR FLECHT DATA