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

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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 December 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

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I. Transient Pressure Drop Investigation

Oscillatory Flow Experiments

The transient pressure drop apparatus is now operated by discharging heated Freon 113 from a large storage accumulator to the test lines. 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.

During this quarter, a new test section was installed. The section contained a 1/2 in. thick plate in which a single hole had been drilled. Oscillatory flow experiments were conducted and the displacements between the flow and pressure drop curves were observed over a wide range of α . Fig. 1 compares the experimental results obtained with predictions obtained from the method of impedance⁽¹⁾⁽²⁾. It can be seen that the general trend is predicted

but that there is very bad scatter in results at low void fractions.

When an attempt was made to repeat the measurements, it was discovered that the piston of the upstream accumulator was no longer sealing. The apparatus was therefore shutdown for repairs.

Blowdown Experiments

It is planned that future experiments emphasize blowdown operation. Planning of these tests has begun.

II. Two-Phase Pressure Drop and Flow Pattern Study

These experiments, which are conducted in a circulating loop using Freon 113, have measured pressure drop across abrupt area changes. Pressure drops across two test sections, each with widely separated expansion and contraction, were previously studied. There is some indication in the literature⁽³⁾ that the equation applying to widely separated area changes does not apply to restrictions in which the contraction and expansion are brought in close proximity. A series of experiments to determine the effect of the length separating the area changes are now being conducted.

In the previous quarter, experiments were conducted with a test section having a two inch length between area changes. No significant difference between these data and those taken earlier were observed.

During this quarter, test data were obtained across a test section having a $\sigma = 0.56$, small pipe size of 3/4 in. and a 0.5 in. length between area changes. Fig. 2 and 3 show the data obtained. It is clear that these data are substantially below the model found to correlate the data obtained with well separated area changes. It is planned to conduct the next set of tests with a restriction placed in a plate approximately 0.2 in. thick.

Improved Correlation of Contraction Data

Efforts continued to improve the correlation of data previously obtained across well separated area changes. The correlation of contraction pressure drops was found to be somewhat improved by slightly changing the method for computing the void fraction at the vena contracta. It is now recommended that, α_3 , the void fraction at the vena contracta be obtained from

$$\alpha_3 = \alpha_{\text{homog}} \quad \text{for } \alpha_{\text{exit}} \leq 0.5 \quad (1)$$

$$\alpha_3 = \alpha_{\text{slip}} + k(\alpha_{\text{homog}} - \alpha_{\text{slip}}) \quad \text{for } \alpha_{\text{exit}} > 0.5$$

where $k = 1.5 - \alpha_{\text{exit}}$

The above equation replaces Equation (4) of the previous quarterly report (COO-2152-13). Equation (3) of that report remains unchanged.

It is hoped that an expression can be determined for the variation of α_3 with distance between area changes as well as void fraction.

III. Transition Boiling and Reflood Heat Transfer Tests

These experiments are being conducted in a heat transfer loop using hot mercury as the heat source. Boiling of water occurs in an annulus around the vertical pipe containing the mercury. Visual observation is possible since the outer pipe of the annulus is of glass. A diagram of the test section is shown in Fig. 4.

Transition Boiling Heat Transfer Data

In the previous quarterly report, the raw data obtained over mass flow rates ranging from about 1×10^4 to 3×10^4 lbs/hr ft² were shown. It was

pointed out that the heat fluxes shown were based on the measured mercury ΔT 's without correcting for the fact that some thermocouples may not have been at the centerline of the mercury stream. Since the radial temperature difference is of the same order of magnitude as the temperature difference between couples spaced axially 4 in apart, these temperature corrections are significant. The temperature difference corrections required were determined by examining non-boiling data where a constant overall U may be expected at all elevations. The temperature difference correction factors so determined were then used in the boiling data calculations.

The heat transfer coefficients obtained for the lowest flow rates are shown in Fig. 5 as a function of $(T_w - T_{sat})$. The qualities associated with these heat transfer coefficients are shown in Fig. 6. It is interesting to note that the nucleate boiling coefficients are in reasonably good agreement with the empirical equation of McAdams et al.⁽¹⁴⁾ for flow boiling at low pressures.

The heat transfer coefficients obtained at the higher flow rates are shown in Fig. 7 and the associated equilibrium qualities in Fig. 8. The nucleate boiling data near the critical heat flux tend to scatter more and lie below the McAdams' curves. At the qualities and velocities used, nucleation suppression, as determined by Chen's correlation⁽⁵⁾ account for only a portion of the observed change.

The peak heat transfer coefficients reached are far below that reached in pool boiling at the same pressure. This is not surprising since the void fraction, α , is in excess of 0.9 under present peak conditions. Avedisian and Griffith⁽⁶⁾ found that, at low liquid velocities, the critical heat flux, q''_{CHF} , attained with boiling Freon was a function of void fraction. They plotted their data in

terms of q''_{CHF}/q''_{max} where q''_{max} is the critical heat flux attained in pool boiling. It was previously noted [Quarterly Progress Report, Period Ending June 30, 1974, C00-2152-12] that, when the critical heat flux data from the present investigation was plotted in this manner, it was consistent with the plot of Avedisian and Griffith⁽⁶⁾.

Preliminary Data Correlation

In a previous report [Quarterly Progress Report, Period Ending March 31, 1973, C00-2152-7] the available transition boiling data, nearly all at high pressures, were correlated by assuming

$$h_{tb} = h_c + h_b$$

where h_c is the convective component of h and h_b is the boiling component of h . The convective h_c (very low for present conditions) was correlated by a modification of Quinn's equation⁽⁷⁾. The boiling component was correlated by the expression

$$\frac{h_b}{Sh_m} = 0.5 \{ \exp[-.0078(\Delta T_{sat})] + \exp[-.0698 (\Delta T_{sat})] \} \quad (2)$$

where

h_m = maximum value of boiling h

S = boiling suppression factor from correlation of Chen⁽⁵⁾

$$\Delta T_{sat} = T_{wall} - T_{sat} \text{ (}^\circ\text{F)}$$

In correlation the previous data it was assumed that the peak heat transfer coefficient was Sh_m and h_m was the value obtained from pool boiling data.

Equation (2) was used for a preliminary correlation of the present data. However, the value of h_m was obtained by taking q_{CHF}/q_{max} from the curve of Avedisian and Griffith⁽⁶⁾ and dividing by the ΔT_{sat} given by McAdams equation. Fig. 9 compares the transition boiling data against this correlation. Reasonable agreement is attained at low and moderate ΔT 's but a significant deviation is observed at high temperature differences.

Tong and Young⁽⁸⁾ have suggested that the quality to be used in correlating transition boiling data obtained in annuli should be that close to the hot wall. This quality they believed would be significantly higher than the equilibrium quality. This effect may provide a partial explanation of the deviations observed at high temperatures (and high qualities).

Equipment Modifications

In order to extend the range over which transition boiling heat transfer data can be taken, the heat transfer apparatus is now being modified. A stainless steel bellows will replace the teflon bellows used to accommodate differential expansion between the glass and steel. This will allow operation at higher pressures. In addition, the upper portion of the heat transfer surface is being insulated. This will allow higher wall temperatures to be attained.

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- (3) Janssen, E., "Two Phase Pressure Loss Across Abrupt Contractions and Expansions - Steam Water at 600-1400 Psia," International Heat Transfer Conference, Vol. 5, p. 13, ASME (1966).
- (4) McAdams, W.H. et al., Ind. Eng. Chem. 41, 1945 (1949).
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- (6) Avedisian, C.F. and P. Griffith, "Critical Heat Flux in Countercurrent Flow," Report No. 80620-84, Eng. Projects Lab, Dept. of Mech. Eng. MIT (1974).
- (7) Quinn, E.P., ASME Paper 66 WA/HT/36 (1966).
- (8) Tong, L.S. and J.D. Young, "A Phenomenological Transition and Film Boiling Heat Transfer Correlation," Proc. of 5th Int. Heat Transfer Conf., Tokyo (1974).

Fig 1

SINGLE ORIFICE TEST SECTION

PHASE SHIFT

$$G = 8.4 \times 10^5 \text{ lb/hr ft}^2$$

$$d/D = .5/1.049$$

Upper Curve : Higher frequency

Lower Curve : Lower frequency

Sonic Velocity: as obtained from Fig 9.12
of 'One dimensional Two-phase flow'
by Wallis

FIGURE 2

RATIO OF TWO PHASE TO SINGLE PHASE
PRESSURE LOSS ACROSS A 1/2 INCH
LONG CONTRACTION-EXPANSION
GEOMETRY AT 60 PSIG

$$\gamma = .56$$

$$\Delta G = 2.0 \times 10^6$$

$$\circ G = 2.4 \times 10^6$$

46 0780

K&E 10 X 10 TO THE INCH • 7 X 10 INCHES
KEUFFEL & ESSER CO. MADE IN U.S.A.

FIGURE 3

RATIO OF TWO PHASE TO SINGLE PHASE
PRESSURE LOSS ACROSS A 1/2 INCH
LONG CONTRACTION-EXPANSION
GEOMETRY AT 40 PSIG

$$V = .56$$

$$\Delta G = 2.0 \times 10^6$$

$$O G = 2.4 \times 10^6$$

46 0780

Fig. 4. Test Section Detail

Fig. 5. h Vs. $(T_{WL} - T_{SAT.})$

Fig. 6 X_E Vs. ΔT_{SAT}

X_E

ΔT_{SAT} ($^{\circ}F$) $\rightarrow$

2-18.3

Fig. 7 h Vs. ($T_{WL} - T_{SAT}$)

h (BTU/hr ft² °F)

- ⊗ $G_w = 17200$ lbm/hr ft²
- $G_w = 20475$ —" —
- △ $G_w = 34440$ —" —

Mc ADAMS Eqn.

Semi-Logarithmic
3 Cycles x 10 to the 0 inch

100 ($T_{WL} - T_{SAT}$) °F → 200 300

Fig. 8 X_E Vs. $(T_{WL} - T_{SAT})$

FIG. 9. COMPARISON OF PREDICTION AND EXPERIMENTAL RESULTS

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