MASTER

COO-926-31
CONF-537-1
USAEC - Euratom Conference

Facsimile Price \$ 1.60

Microfilm Price \$.80

Available from the
Office of Technical Services
Department of Commerce
Washington 25, D. C.

on

Two-Phase Flow Problems

Meeting in Washington, D. C., April 29, 30, May 1, 1964

Two-Phase Flow Through Apertures¹

H. S. Isbin, Dept. Chem. Eng., Univ. of Minnesota, Minneapolis, Minnesota

Apertures are defined as any type of opening varying from sharp-edged orifices to tapered and contoured sections including short tubes ($L/D < 4$). The studies of two-phase, steam-water flows through apertures are aimed at acquiring a better understanding of the phenomena associated with "loss-of-coolant accidents" and the release rates of coolant from breaks in the reactor vessel and piping. Details of the flows in apertures are being investigated experimentally and are being coupled with analytical models to yield predictive methods.

¹Other studies in progress not included in this report are concerned with the "burnout crisis".

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

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.

Experimental Equipment

A sketch of the experimental equipment is given in Figure 1 and a photograph of the assembly is presented in Figure 2. The equipment is designed to produce abruptly an "opening" in a tank containing subcooled or saturated water (up to 250 psig), and to measure the flow rates and thrusts produced over the period of the test. Test duration varies from about 10 seconds (for a 1-inch dia. opening) to several minutes and a "steady-state" flow is attained by maintaining a constant tank pressure through regulation of a compressed air input. The air-water contact is minimized through use of a baffle in the tank. The tank is suspended from a load cell and flexible connectors are used for all pipe line connections. The thrust is measured by a second load cell, mounted diametrically opposite the opening. Heaters are provided in the tank for bringing the water to the boiling point and to the desired pressure. Calibrated thermocouples are used to measure the temperature of the water in the tank, and transducers are used to measure the pressures, including pressures inside the apertures.

Figure 3 illustrates the types of apertures used. Apertures A and B function as sharpened-edged orifices for cold water, but not for saturated water. The geometrical variations in apertures 1, 2 and 3 provide stringent tests for the model studies. Thin brass shims are used to seal the apertures. Flow through the apertures is initiated by rupturing the shim with a circular knife.

All output signals from the load cells and the pressure transducers are recorded on a visicorder oscillograph.

Test Results

The results of all tests to-date with saturated water in the tank indicate that no flashing occurs within the tank even though the accelerating flows lead to marked decreases in pressure in the neighborhood of the aperture. Figure 4 illustrates calculated pressure profiles for an ideal, single-phase fluid at the opening and in the tank near the opening. The system pressure in the tank is taken as P_o (gauge) and the pressure outside the opening is taken as zero. The fractional drop in pressure, $(P_o - P)/P_o$, is plotted for both a circular opening as well as for a two-dimensional (2 - D) opening. No special precautions have been necessary for the water treatment in order to obtain reproducible results. The interpretation that no flashing occurs within the tank is based upon results which are presented for the various apertures. Cold water runs have been used to test the reliability of the weight and thrust measurements and typical results are given in Figures 5 and 6 for aperture B.

The flow of saturated water, from about 40 psig to 200 psig, through a variety of apertures is illustrated in Figures 7 through 10. For apertures 1, 2 and 3, pressure measurements within the aperture indicate a backpressure P_b which is almost constant over the length of the aperture. Use of this pressure in the usual orifice equation,

$$G = 0.61 \sqrt{2g_c (P_o - P_b)/v}$$

accurately predicts the measured mass flow rates. Figures 8a, 9a and 10a present the experimental and calculated mass flow rates. The use of the orifice equation for single phase flow (with v as the specific volume of liquid water at the initial saturation pressure) in accurately calculating the mass flow rates implies that no vaporization is occurring within the tank.

The liquid forms a jet of superheated liquid within the aperture. Furthermore, the use of the coefficient 0.61 indicates that the vena contracta of the superheated jet follows the behavior of a single-phase fluid.

The thrust measurements also serve to verify that only a liquid jet is produced at the opening of the aperture. Figures 8b, 9d, and 10d illustrate the magnitude of the various terms involved in the thrust measurements. The equations used are presented in an appendix. One should recognize that with the tapered openings, apertures 1 and 2, very significant contributions are made to the thrust by the pressure forces within the aperture. Note further, that the portion of the overall thrust contributed by the mass flow may be relatively small. An additional force is contributed by the pressure on the downstream side of aperture 3 resulting from the confinement of the resulting jet by the knife used to rupture the aperture seal.

Breakup of the superheated liquid jet begins to occur within the aperture and a backpressure, P_b , is created. Under some circumstances (see Argonne's report), the ratio of the backpressure P_b to the tank pressure P_0 is independent of the tank pressure P_0 . For aperture 2, the value is 0.3 and use of the ratio reduces the orifice equation to

$$G = (0.61) \sqrt{(2g_c)(0.70)P_0/v} = 49.1 \sqrt{P_0/v} \text{ (lb}_m\text{/secft}^2\text{)}$$

Comparison of this equation with the measured values is shown in Figure 9c. The pressure ratio in aperture 3, shown in Figure 10c, undergoes a slight reduction with increasing tank pressure.

Model Studies

Several models are under investigation involving the equations of continuity, momentum and energy. The backpressure, thrust, and mass flow rates provide checks for the calculations. The goal sought is a predictive method for the backpressure so that the mass flow rate through a variety of apertures can be estimated. The studies noted are for short apertures ($L/D < 4$). With longer apertures and tubes ($L/D > 12$), the Fauske model may be used to predict the critical flow at the exit.

A summary of the pertinent literature is contained in a paper prepared for the Third United Nations Conference on the Peaceful Uses of Atomic Energy, August 31 to September 9, Geneva, Switzerland:

"Critical Flow Phenomena In Two-Phase Mixture and Their Relationships to Reactor Safety" - H. S. Isbin, H. K. Fauske, M. Petrick, C. H. Robbins, R. V. Smith, S. A. Szawlewicz, and F. R. Zaloudek.

Appendix

For the case of a single-phase, incompressible fluid flowing through a sharp-edged orifice, a relation obtained for the average pressure difference across the opening is

$$\overline{\Delta P_a} = 0.54 (P_o - P_b)$$

where P_o is the pressure within the tank and P_b is the pressure surrounding the downstream side of the orifice (backpressure). The coefficient α is used to relate the use of the mass average velocity with the proper momentum outflow through the orifice or aperture.

$$\alpha = \frac{\iint \rho (U \cos \theta)^2 dA_a}{\rho \bar{U}^2 A_a}$$

where U = magnitude of the velocity vector

$\cos \theta$ = orientation of the velocity vector at the aperture

A_a = cross-sectional area of aperture

$$W = \text{mass flow rate} = \iint_{A_a} \rho U \cos \theta dA_a = \bar{\rho} \bar{U} A_a$$

$$\bar{U} = \text{mass average velocity} = \frac{\iint \rho U \cos \theta dA_a}{\bar{\rho} A_a}$$

$\bar{\rho}$ = average fluid density (constant for case considered)

The coefficient has been evaluated as $\alpha = 0.91$.

The values obtained for $\bar{\Delta P}_a$ and for α for the single-phase, incompressible fluid flowing through a sharp-edged orifice may also be applied for the test results involving the tank of saturated water and the resulting flows through the apertures. The justification for this step is that the mass flow rates follow the single-phase orifice equation and thus form a superheated liquid jet within the aperture. Partial breakup of the jet occurs within the aperture. One form of the momentum balance for flow through the aperture yields

$$T = \frac{\alpha \bar{\rho} \bar{U}^2 A_a}{g_c} + A_a \bar{\Delta P}_a + A_t \bar{\Delta P}_w$$

where T = thrust

A_t = projected wall area of the aperture ^{normal} parallel to the flow

$\bar{P}_w$ = average pressure within the aperture (as measured along the aperture walls)

$$\Delta \bar{P}_w = \bar{P}_w - P_{atm}$$

$\frac{\alpha \bar{p} \bar{U}^2 A}{\epsilon_c} =$ force produced by the momentum outflow of the superheated liquid jet through the opening of the aperture

$A_a \Delta \bar{P}_a =$ force due to the pressure at the opening of the aperture

$A_t \Delta \bar{P}_w =$ force due to the backpressure acting on the tapered walls of the aperture.

TO: [illegible]

FROM: [illegible]

SUBJECT: [illegible]

RE: [illegible]

DATE: [illegible]

TIME: [illegible]

BY: [illegible]

FOR: [illegible]

THROUGH: [illegible]

List of Figures

- Figure 1. Sketch of U of M Experimental Equipment for Measurement of Two-Phase Flow Through Apertures
- Figure 2. Photograph of U of M Experimental Equipment for Measurement of Two-Phase Flow Through Apertures
- Figure 3. Apertures Used For the U of M Two-Phase Flow Tests
- Figure 4. Pressure Profiles For Ideal, Single-Phase Fluid Flow Through Circular and Two-Dimensional Openings
- Figure 5. Cold Water Flow Through a $1/2$ - in.dia. Orifice
- Figure 6. Thrust Produced By Cold Water Flow Through a $1/2$ - in.dia. Orifice
- Figure 7. Flow of Saturated Water Through Apertures A and B
- Figure 8. Flow of Saturated Water Through Aperture 1. a) Mass Flow Rate vs Pressure Difference. b) Comparison of Measured and Calculated Thrusts
- Figure 9. Flow of Saturated Water Through Aperture 2. a) Mass Flow Rate vs. Pressure Difference. b) Constancy of Pressure Ratio, P_b/P_o . c) Comparison of Experimental and Calculated Flow Rates Using $P_b/P_o = 0.3$. d) Comparison of Measured and Calculated Thrusts
- Figure 10. Flow of Saturated Water Through Aperture 3. a) Mass Flow Rate vs. Pressure Difference. b) Pressure Measurements Within Apertures. c) Exit Pressure Ratio vs. Tank Pressure. d) Comparison of Measured and Calculated Thrusts.

Fig. 1.

Fig. 2.

Fig. 3.

Fig. 9a.

Fig. 9c.

Fig. 9b.

Fig. 9d.

Fig. 10a.

Fig. 10c.

Fig. 10b.

Fig. 10d.