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EXPERIMENTS ON THE ONSET OF GAS PULL-THROUGH DURING DUAL DISCHARGE FROM A RESERVOIR

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Abstract—The phenomenon of gas pull-through is investigated experimentally for the condition of simultaneous discharge from two small orifices (6.35 mm i.d.) located on the side of a high-pressure reservoir containing a stratified air–water mixture. The critical height corresponding to the onset of gas pull-through is found to be a function of the two discharge rates and the vertical distance separating the centrelines of the orifices. Experimental results pertaining to the appearance of the phenomenon and the critical height are presented for a wide range of the aforementioned independent parameters. Based on these results, an empirical correlation is developed for predicting the data with a high degree of accuracy.

Key Words: gas pull-through, dual discharge, experimental

1. INTRODUCTION

Studies of two-phase flow through small breaks in horizontal pipes under stratified-flow conditions have gained importance due to their relevance to nuclear reactor safety during postulated loss-of-coolant accidents (LOCA). Zuber (1980) pointed out that during such flows two distinct phenomena may occur, depending on the location of the gas–liquid interface relative to the break. If the break is located above the horizontal interface, liquid can be entrained in the predominantly gas flow through the break (liquid-entrainment phenomenon). On the other hand, if the break is located below the horizontal interface, gas can be pulled through the break by a vortex or vortex-free motion (gas pull-through phenomenon). Based on the existing literature at that time, which did not include information on these phenomena for conditions simulating the cooling system of nuclear reactors, Zuber (1980) reported that the onsets of both liquid entrainment and gas pull-through may be correlated by an equation of the form

$$h/d = a\,\mathrm{Fr}^b, \qquad [1]$$

where h is the vertical distance between the interface and the centreline of the break, d is the diameter of the orifice simulating the break, a and b are constants whose values depend on the type of phenomenon and physical arrangement, as shown in table 1, while Fr is the Froude number, given by

$$\mathrm{Fr} = V_c\sqrt{\rho_c}/\sqrt{g\,d\,\Delta\rho}, \qquad [2]$$

Table 1. Values of a and b reported by Zuber (1980) for [1]

Phenomenon	Physical arrangement	a	b	Source
Liquid entrainment	Withdrawal from a large reservoir through a side orifice	0.624	0.4	Craya (1949) and Gariel (1949)
	Withdrawal from a large reservoir through a side slot	0.756	0.667	Craya (1949) and Gariel (1949)
	Withdrawal from a large reservoir through a vertical pipe	0.419	0.5	Rouse (1956)
Gas pull-through	Vortex-free withdrawal from a tank through a bottom orifice			Lubin & Hurwitz (1966)
	$h/d < 1$	0.574	0.667	
	$h/d > 1$	0.624	0.4	

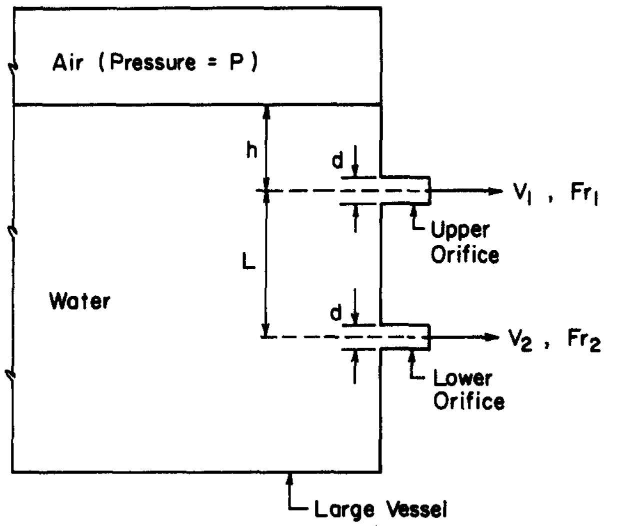

Figure 1. Geometry and flow parameters.

where V_c is the velocity of the continuous phase through the orifice (which is the gas during liquid entrainment and the liquid during gas pull-through), ρ_c is the density of the continuous phase, $\Delta\rho$ is the density difference between the phases and g is the gravitational acceleration.

The importance of these phenomena due to their relevance to fluid distribution in the cooling system during a LOCA has motivated experimental investigations using physical arrangements more relevant to nuclear reactors. Crowley & Rothe (1981) tested a simulated break (an orifice of dia d = 6.35 mm) in a horizontal pipe of dia $D = 76.2$ mm using horizontal, vertical upward and vertical downward orientations of the break. With a stratified air–water mixture in the pipe at an operating pressure of 270–310 kPa discharging directly to the atmosphere, they were able to measure the value of h/d at which each phenomenon was first observed. The deviation between the measured values of h/d and the predictions of [1] ranged from 16 to 32% for the different phenomena. Results were also reported by Smoglie & Reimann (1986) and Smoglie *et al.* (1987) using stratified air–water flow at 500 kPa in a horizontal pipe ($D = 0.206$ m) with different break sizes ($d = 6, 8, 12$ and 20 mm) and different orientations for each break. Flow through the break was controlled by a throttle valve. These results indicate an insignificant effect of the break size on the onsets of liquid entrainment and gas pull-through. A general correlation was developed in the form of [1] imposing $b = 0.4$ for all data and determining an average value of the coefficient a for each phenomenon. For liquid entrainment from top orifices ($a = 1.516$) and gas pull-through from bottom orifices ($a = 1.816$), the deviation from the corresponding values in table 1 is large. However, the results for liquid entrainment ($a = 0.626$) and gas pull-through ($a = 0.681$) from side

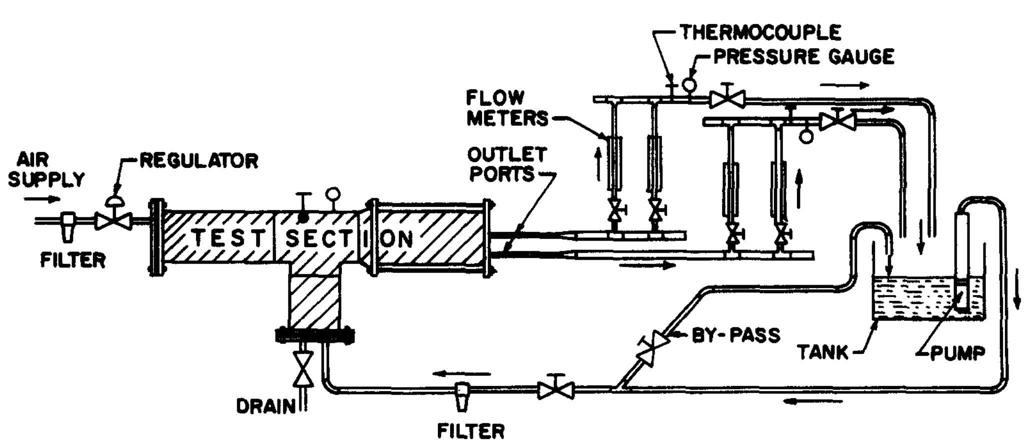

Figure 2. Schematic diagram of the experimental rig.

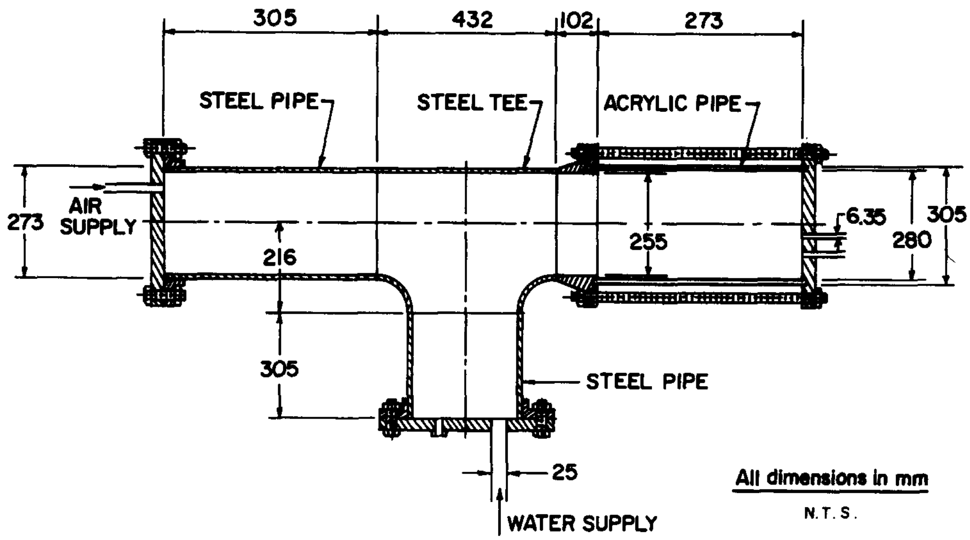

Figure 3. Cross-sectional view of the test section.

orifices are in good agreement with those in table 1. The experiments reported by Crowley & Rothe (1981), Smoglie & Reimann (1986) and Smoglie *et al.* (1987) introduced factors which were not present in the physical arrangements listed in table 1, such as pipe curvature, system pressure and superimposed main pipe flow.

A common feature among the above investigations is that fluid discharge was always induced through a single orifice. In situations where multiple discharge takes place simultaneously from several orifices at the same pipe cross-section, such as the case with the flow distribution headers of CANDU nuclear reactors, the existing correlations for the onsets of liquid entrainment and gas pull-through may not apply. The CANDU heat transport system contains large horizontal headers (approx. 6 m long and 0.325 m dia) connected to the fuel channels by a number of feeders (typically 50.8 mm dia) attached to the side walls of the header. Normally, the feeders are arranged

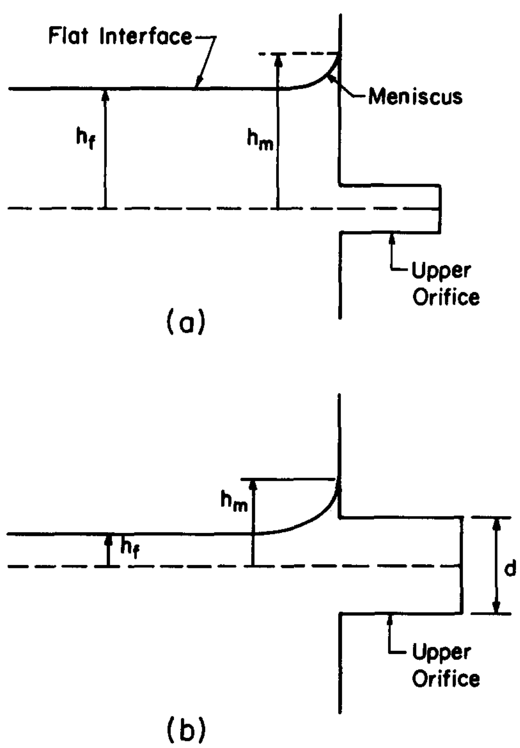

Figure 4. Definition of h_m and h_f.

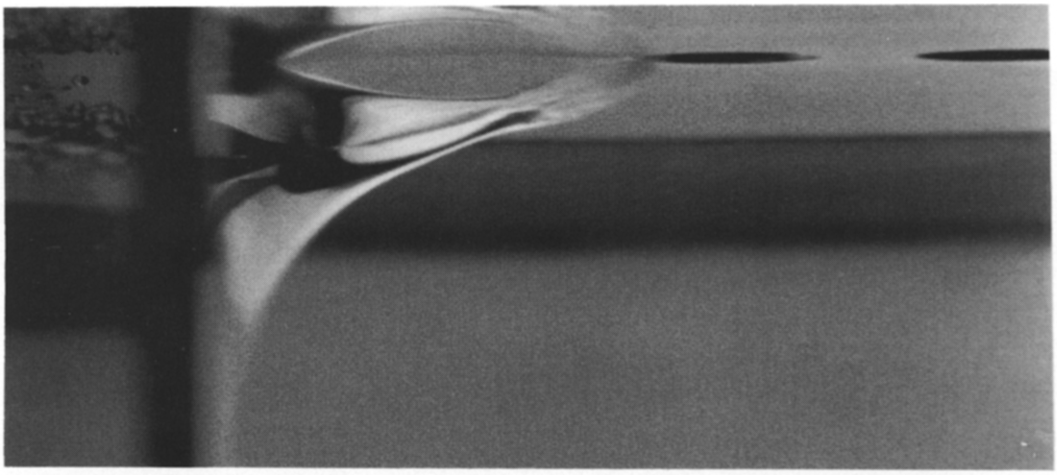

Figure 7. Gas pull-through at the upper orifice.

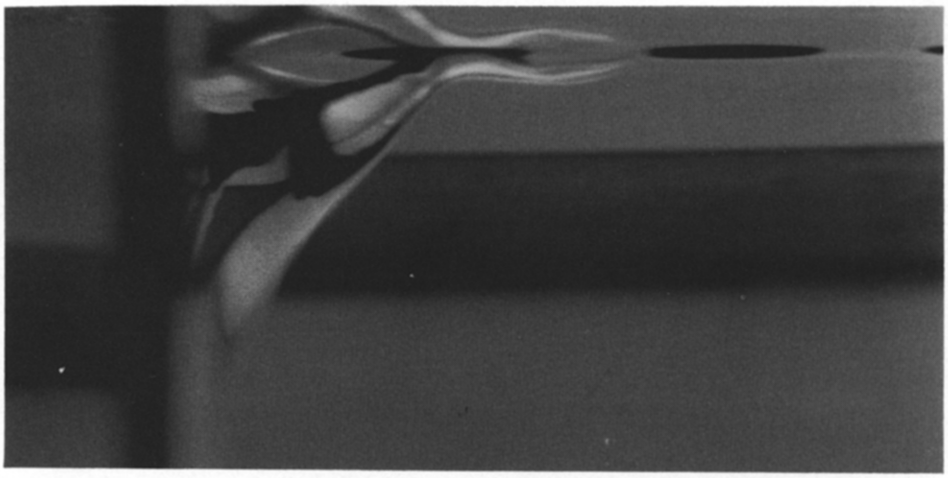

Figure 6. Gas pull-through at both orifices.

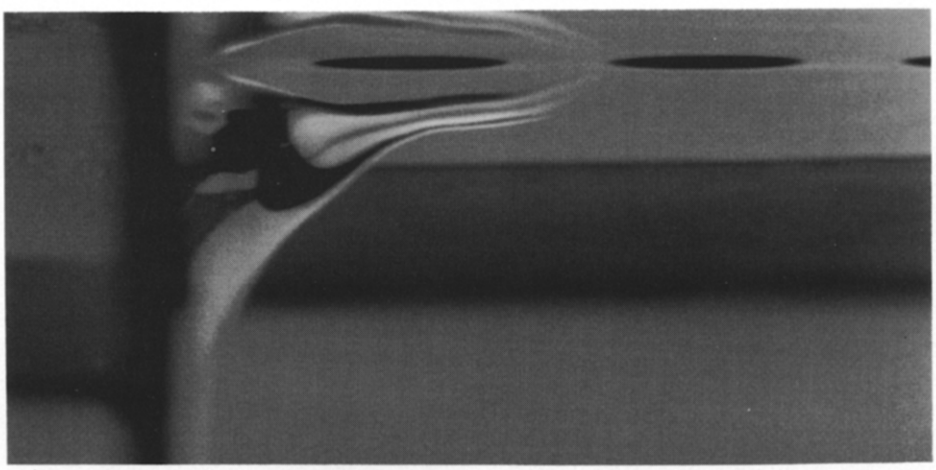

Figure 5. Gas pull-through at the lower orifice.

in banks at different cross-sections along the header with five feeders in each bank. In a recent investigation by Kowalski & Krishnan (1987) using steam–water flow in a large manifold typical of the CANDU reactor header–feeder system, it was found that the experimental values of h/d at the onsets of liquid entrainment and gas pull-through were significantly underpredicted by the correlations of Smoglie & Reimann (1986) and Smoglie *et al.* (1987).

In the present investigation, a basic experiment was conducted in order to study the phenomenon of gas pull-through during discharge from a large reservoir through two side orifices of the same diameter d, separated by a vertical distance L centre-to-centre. This experiment is obviously a first step towards understanding situations of multiple two-phase discharge at the same cross-section. The main question to be answered is what are the influences of the separating distance L and the rate of flow from the lower orifice on the onset of gas pull-through from the upper orifice? The possibility of simultaneous gas pull-through at both orifices is also explored. A general correlation of the data is presented and shown to be capable of accurate predictions.

2. EXPERIMENTAL INVESTIGATION

2.1. Experimental parameters

Figure 1 shows a schematic diagram of the experiment and defines the relevant geometrical and flow parameters. Two small orifices are placed on the side of a large reservoir containing stratified layers of air and water at a pressure P. Controllable amounts of water are withdrawn with velocities V_1 and V_2 from the upper and lower orifices, respectively. The corresponding values of the Froude number are Fr_1 and Fr_2. With these rates of flow, and for given values of L and d, there is a critical height h at which gas pull-through begins to take place.

Based on a simple dimensional analysis of the problem, neglecting the effects of viscosity and surface tension, it is possible to identify h/d, L/d, Fr_1 and Fr_2 as the only relevant dimensionless groups. Therefore, the correlation for the onset of gas pull-through is expected to take the form,

$$h/d = f(\mathrm{Fr}_1, \mathrm{Fr}_2, L/d). \qquad [3]$$

It is reasonable to expect that h/d would increase with an increase in either Fr_1 or Fr_2, or a decrease in L/d. Also, the form of [3] should be such that it reduces to the special case given by [1] as $\mathrm{Fr}_2 \to 0$ or $L/d \to \infty$. Another constraint on the mathematical form of [3] is that for $L = 0$, Fr_1 and $\mathrm{Fr}_2 \neq 0$, [3] must reduce to [1] with $\mathrm{Fr} = \mathrm{Fr}_1 + \mathrm{Fr}_2$.

When gas pull-through begins to take place, there are three possible forms for its appearance. At the onset, the gas may be pulled towards the upper orifice only, the lower orifice only or both

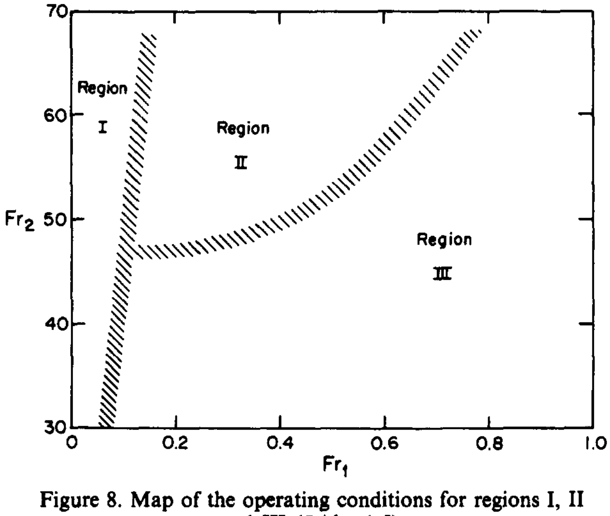

Figure 8. Map of the operating conditions for regions I, II and III ($L/d = 1.5$).

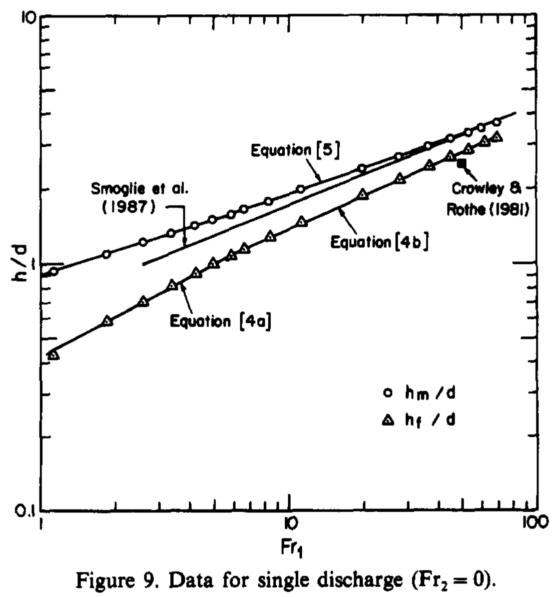

Figure 9. Data for single discharge ($\mathrm{Fr}_2 = 0$).

orifices simultaneously. The boundaries of the operating zone for each of these forms are expected to depend on the values of Fr_1, Fr_2 and L/d.

2.2. Experimental apparatus

A schematic diagram of the flow loop is shown in figure 2. An immersion-type circulating pump was used to supply distilled water to the test section at a rate controlled by a by-pass line. The test section was connected to an air supply with a pressure regulator which maintained a steady pressure of 510 kPa throughout the experiment. Rate of discharge from the test section through each of the two outlet ports was measured by two water flowmeters with overlapping ranges. The maximum capacities of the flowmeters on each outlet line were 69 and 690 cm^3/s; thus, flow rates within the range 6.9–690 cm^3/s were measured with accuracy. The rate of discharge through each line was controlled by throttling valves upstream of the flowmeters. Discharged water was finally returned to a receiving tank, as shown in figure 2.

The temperature and pressure within the test section, as well as at some other locations within the loop, were monitored during the experiment. All flowmeters, thermocouples and pressure gauges were calibrated before testing began.

Details of the test-section design are shown in figure 3 with water entering through the bottom flange, air through the left flange and discharge through the right flange. Schedule 80 steel sections were used in the construction, except for a clear acrylic pipe section near the outlet flange for visual observation of the phenomenon. The discharge orifices were holes, 6.35 mm dia and 127 mm long, machined in a brass block and bolted on the outlet flange. Thus, each orifice had a straight length of 20 dia before any bends or area changes were incorporated. The holes were machined to provide $L/d = 1.5$, 2, 3, 4 and 6. After installing the brass block on the outlet flange, a surveying transit was used to ensure that the faces of the flange and the block were vertical and that the centrelines of the orifices fell on a straight vertical line.

Two pressure taps (not shown in figure 3), one on the air side the other on the water side, were installed on the outlet flange and connected to a differential pressure transducer in order to measure the liquid height in the test section. It was noted during the early stages of the experiment that a meniscus forms along the outlet flange due to surface tension and that the height of this meniscus, even though small in absolute terms (about 3.3 mm), is quite significant relative to orifice diameter. Therefore, it was decided to record each datum point in terms of both h_m and h_f, where h_m is the height of the tip of the meniscus above the centreline of the upper orifice and h_f is the height of the flat interface above the centreline of the upper orifice, as illustrated in figure 4(a). It is conceivable, and was actually observed, that at low discharge rates, gas pull-through at the upper orifice may occur with the flat interface below the top edge of the orifice (i.e. $h_f/d < 0.5$) while the meniscus covers the orifice completely (i.e. $h_m/d \geqslant 0.5$), as shown in figure 4(b). For low liquid heights associated with small discharge rates, h_m is probably more meaningful to the phenomenon than h_f, while for large discharge rates, the difference between h_m/d and h_f/d is relatively small. Two readings of the differential pressure transducer were carefully determined, one corresponding to the

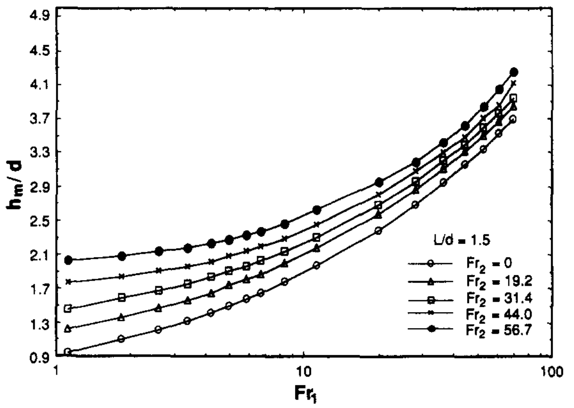

Figure 10. The influence of Fr_2 during dual discharge for $L/d = 1.5$.

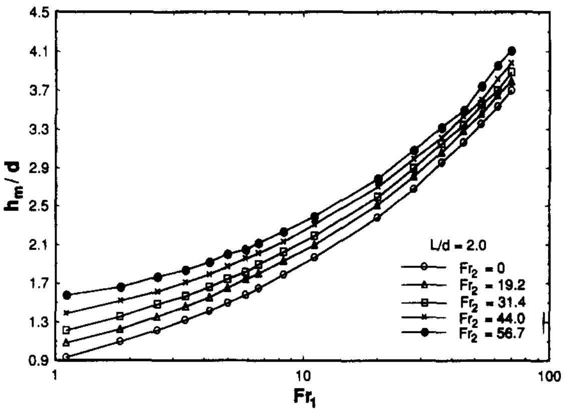

Figure 11. The influence of Fr_2 during dual discharge for $L/d = 2$.

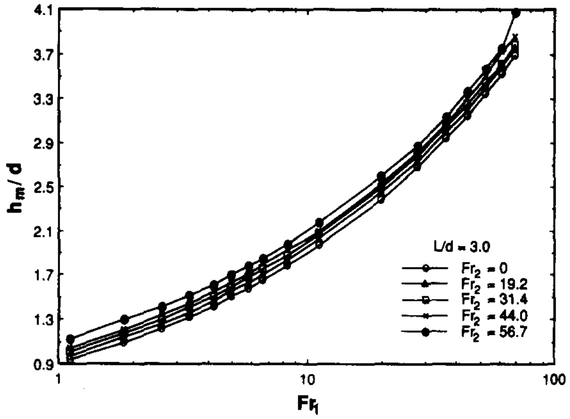

Figure 12. The influence of Fr_2 during dual discharge for $L/d = 3$.

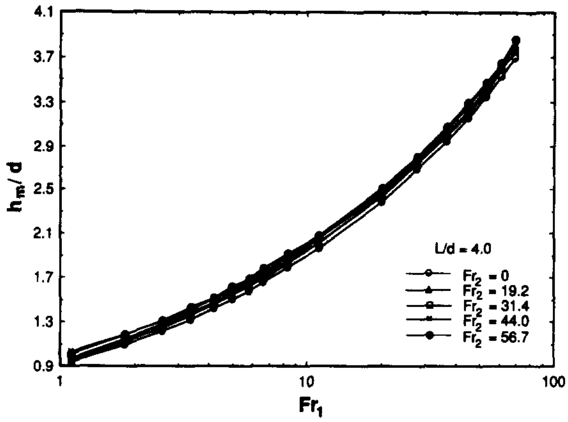

Figure 13. The influence of Fr_2 during dual discharge for $L/d = 4$.

situation where the tip of the meniscus was aligned with the centreline of the upper orifice and the second corresponding to the situation where the flat interface was aligned with the centreline of the upper orifice. These two readings established the location of the centreline of the upper orifice and the height of the meniscus.

2.3. *Experimental procedure*

The testing program was designed to provide quantitative assessment of the influences of L/d and Fr_2 on the onset of gas pull-through over a wide range of Fr_1. Thus, five different values of Fr_2 were used with each L/d and for each combination of L/d and Fr_2, several data points were generated covering the widest possible range of Fr_1. The following procedure was followed for each datum point:

1. Water was pumped into the test section until a high level was achieved.
2. Air pressure was applied and maintained steady at 510 kPa.
3. Water flow through the outlet orifices was initiated and the desired values of Fr_1 and Fr_2 were set by adjusting the valves around the flowmeters.
4. Water flow from the pump into the test section was regulated by the by-pass line to a rate slightly lower than the total outlet flow rate through the orifices. As a result, the liquid level in the test section (indicated by the differential pressure transducer) decreased very slowly (at a rate of about 1.5 mm/min).
5. As the gas–liquid interface dropped to a certain level, a sudden formation of gas pull-through was visually observed through the transparent part of the test section. The reading of the pressure transducer was recorded immediately following the onset of the phenomenon from which h_m and h_f were evaluated.

3. RESULTS AND DISCUSSION

About 425 data points (or test runs) were generated in this investigation. The following ranges of geometrical and flow conditions were covered:

$$P = 510\,\text{kPa}$$

$$d = 6.35\,\text{mm}$$

$$L/d = 1.5,\ 2,\ 3,\ 4 \text{ and } 6$$

$$Fr_1 = 0 \text{ to } 70$$

$$Fr_2 = 0,\ 19.2,\ 31.4,\ 44.0 \text{ and } 56.7.$$

3.1. *Flow phenomena*

Throughout this investigation, the gas–liquid interface was smooth and basically free of any ripples. The only exception was a small area of interface close to the discharge orifices where small ripples appeared due to circulation near the onset of the phenomenon. This feature of a smooth interface was useful in eliminating noise from the reading of the differential pressure transducer. Attainment of this favourable interface condition was made possible by a special design of the water inlet to the test section, where the incoming flow was dispersed into a number of horizontal streams, and was also aided by the fact that there was no gas flow within the test section before the onset of the phenomenon.

For given values of Fr_1, Fr_2 and L/d, as the liquid level was slowly lowered, a dip appeared in the interface near the orifices. When a critical liquid level, h, was reached, a gas cone suddenly formed and its tip quickly travelled to one or both discharge orifices. This instant was characterized as the onset of gas pull-through in this investigation. At the onset, the gas cone was sometimes unstable with its tip intermittently detaching from the orifice. However, as the liquid level dropped slightly below h, the cone grew thicker and became more stable.

In most cases, gas was pulled through by a vortex mechanism with spiral-type motion in the liquid surrounding the gas cone. The transition to a vortex-free mechanism (where the component of liquid velocity tangential to the cone vanishes) appears to be mainly dependent on the value of h with vortex flow at high h and vortex-free flow at low h. It was difficult to determine the precise location of this boundary by just visual means.

In order to describe the pattern of gas pull-through, in terms of which of the orifices was active, let us consider the case of a high Fr_2 and very low (or zero) Fr_1. In such a case, gas pull-through was observed at the lower orifice only (region I), as illustrated by the photograph in figure 5. This photograph shows a well-developed gas cone and a part of its reflection (a mirror image) to the right. Maintaining a high Fr_2 and slightly increasing Fr_1, the pattern in figure 6 was observed with gas pull-through taking place at both orifices at the onset (region II). A further increase in Fr_1 caused a shift into region III, where gas was pulled towards the upper orifice only, as illustrated by figure 7. The operating conditions corresponding to these three regions are mapped out in figure 8 for $L/d = 1.5$. It must be pointed out that the transition lines between the regions are, in fact, representative of transition zones with finite widths. This is due to the difficulty in determining the pull-through pattern near the boundaries between regions and the higher uncertainty associated with the very low values of Fr_1 used in this part of the study. In the present experiment, for $L/d = 1.5$ and $Fr_2 < 47$, region II behaviour could not be detected and it appeared that transition occurred directly from region I to region III. Regions I and II are very narrow and they are limited to very small discharge rates from the upper orifice ($Fr_1 < 1$). The flow situations of more practical interest ($Fr_1 > 1$) fall in region III. All the results presented in the following sections belong to that region.

3.2. Single discharge

Experimental results for the special case of extraction through the upper orifice only (i.e. $Fr_2 = 0$) were obtained first and are presented in figure 9. The correlation of Smoglie *et al.* (1987) and the single datum point reported by Crowley & Rothe (1981) for gas pull-through from a horizontal

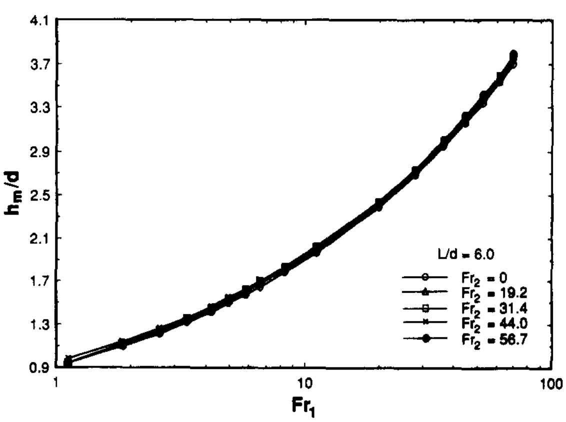

Figure 14. The influence of Fr_2 during dual discharge for $L/d = 6$.

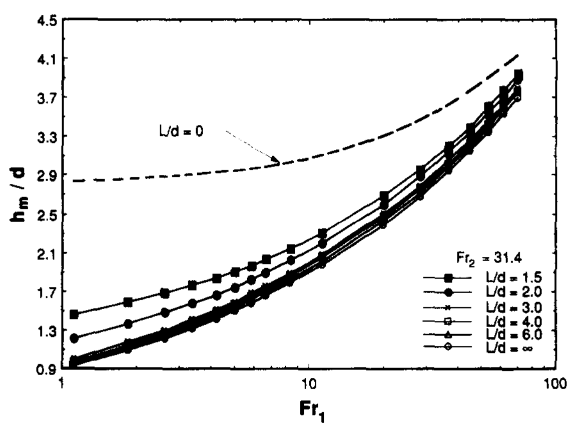

Figure 15. The influence of L/d during dual discharge for $Fr_2 = 31.4$.

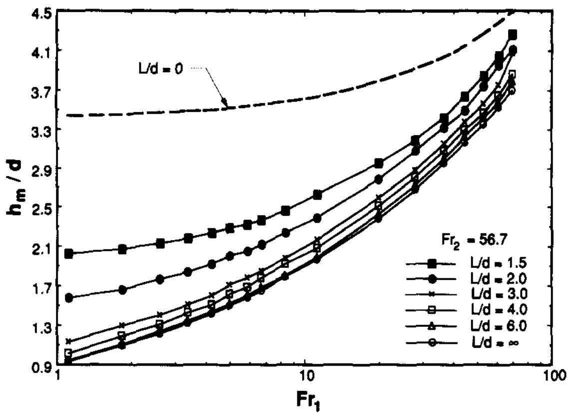

Figure 16. The influence of L/d during dual discharge for $Fr_2 = 56.7$.

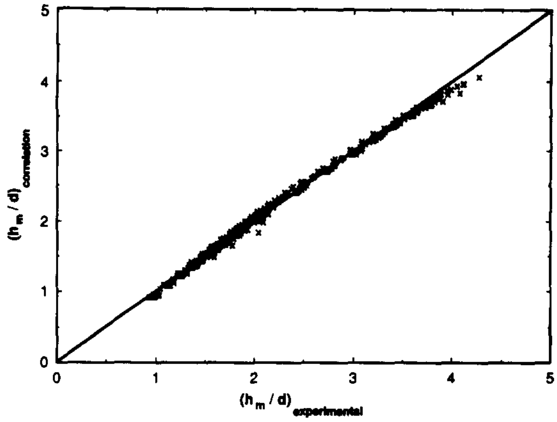

Figure 17. Comparison between the present data and correlation [7].

orifice are shown for comparison. In all the present data, the height of the meniscus ($h_m - h_f$) was estimated to be 3.3 mm based on two different methods of measurement. It is interesting to see the significant effect of this small height on the ratio of h_m/h_f, which can be as high as two at low Fr_1. Therefore, it is recommended that in future experiments of a similar nature, the liquid height be specified in a definite manner.

The following correlations were obtained using standard least-squares fitting:

$$h_f/d = 0.425\, Fr_1^{0.529}, \qquad h_f/d \leqslant 1.15, \qquad [4a]$$

$$= 0.508\, Fr_1^{0.435}, \qquad h_f/d \geqslant 1.15, \qquad [4b]$$

and

$$h_m/d = 0.887\, Fr_1^{0.334}, \qquad \text{for all } h_m/d. \qquad [5]$$

The correlation of Smoglie *et al.* (1987) agrees better with the present results of h_m/d, particularly at high Fr_1 and it deviates by about 20% at $Fr_1 = 2.5$. This is a remarkable agreement in view of the fact that pipe curvature and superimposed main pipe flow are not present in the present experiment. It is also interesting to note that the exponent $b = 0.4$, which was developed theoretically by Craya (1949) for liquid entrainment from a side orifice neglecting the effect of surface tension and used by Smoglie *et al.* (1987) for both liquid entrainment and gas pull-through, falls near the average of the exponents in [4a, b] and [5] which are influenced by surface tension. Figure 9 also shows good agreement between Crowley & Rothe (1981) and the present results for h_f/d.

3.3. Dual discharge

The influence of Fr_2 on h_m/d over a wide range of Fr_1 is shown in figures 10–14 for individual values of L/d. Values of h_f/d will not be presented since they can be easily inferred from h_m/d. Figures 10–14 show that h_m/d generally increases as Fr_2 increases for all Fr_1 and L/d. The percentage increases in h_m/d at any given value of Fr_2 is much more pronounced at low Fr_1 and its drops monotonically as Fr_1 increases. For example, with $L/d = 1.5$ and $Fr_2 = 56.7$, the value of h_m/d at $Fr_1 = 1.1$ is approximately double the value measured with single discharge (i.e. $Fr_2 = 0$), while at $Fr_1 = 69.3$, the increase is only 12.4%.

Considering figures 10–14 comparatively, it is clear that the influence of the second discharge is enhanced as the distance between the orifices is decreased. This is illustrated in figures 15 and 16 for two specific values of Fr_2. These results indicate that, for the range of Fr_1 and Fr_2 covered in this investigation (which is fairly wide), the influence of the second discharge can be ignored for all practical purposes when $L/d > 6$. However, this influence can be significant for lower values of L/d and the magnitude of this influence depends on Fr_1 and Fr_2. The data in figures 15 and 16 labelled $L/d = \infty$ are identical to the data for $Fr_2 = 0$ in figures 9–14. Also for completeness, a dashed line is shown in figures 15 and 16 for the limiting case $L/d = 0$. This bound was obtained from [5] as follows:

$$h_m/d = 0.887\,(\mathrm{Fr}_1 + \mathrm{Fr}_2)^{0.334}, \qquad \text{at } L = 0. \qquad [6]$$

3.4. *General empirical correlation*

An attempt was made to develop a generalized correlation for the onset of gas pull-through from the upper orifice under dual discharge. The following form was assumed:

$$h_m/d = c_1[\mathrm{Fr}_1 + \mathrm{Fr}_2 \exp\{-c_3\,(L/d)^{c_4}\mathrm{Fr}_1^{c_5}\mathrm{Fr}_2^{c_6}\}]^{c_2}, \qquad [7]$$

where c_1 through c_6 are correlating coefficients. This form satisfies the conditions discussed at the end of section 2.1 for the limiting conditions provided that the following constraints on the coefficients are satisfied:

(i) $c_1 = 0.887$ and $c_2 = 0.334$ in order that [7] reduces to [5] as $\mathrm{Fr}_2 \to 0$ and/or $L/d \to \infty$.

(ii) c_4 must be positive in order to be consistent with the experimental trend of increasing h_m/d with decreasing L/d.

Good agreement between data and predictions was obtained with $c_3 = 2.52$, $c_4 = 1.1$, $c_5 = -0.22$ and $c_6 = -0.16$. This agreement, where 98% of the data points are predicted within $\pm 5\%$, is illustrated in figure 17. Correlation [7] is, of course, recommended only for the experimental range covered in this investigation.

4. CONCLUDING REMARKS

A basic experiment has been conducted in order to investigate the phenomenon of gas-pull-through during dual discharge from a large reservoir containing a stratified air–water mixture at 510 kPa. Flow discharge was induced through two small orifices ($d = 6.35$ mm) separated by a variable distance L centre-to-centre. The critical height at the onset of the phenomenon was measured over wide ranges of L/d and the Froude number at the two orifices, Fr_1 and Fr_2. The results indicate that the appearance of the phenomenon and the value of the critical height are strongly dependent on the three independent parameters Fr_1, Fr_2 and L/d. The individual effect of each of these parameters has been illustrated quantitatively and a general empirical correlation [7] has been developed. Since correlation [7] is purely empirical, its use is recommended only with geometries, fluid properties and flow conditions similar to those considered in this investigation.

This investigation was motivated by the need to develop an improved understanding of two-phase flow behaviour in large manifolds such as CANDU reactor headers. However, as stated earlier, the present experiment is only a first step designed to answer the specific questions posed earlier in the paper. Further research involving other geometries, fluid properties and flow conditions must be carried out before complete understanding of the flow distribution in manifolds can be achieved. Nevertheless, the present experiment shows that the onset of gas pull-through from a side orifice can be influenced by flow from other orifices in the same cross-section.

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