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TOP FLOODING IN THIN RECTANGULAR AND ANNULAR PASSAGES

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Abstract—Top flooding experiments in thin rectangular passages of high aspect ratio were conducted to study the basic flooding characteristics and similarities with those in annular passages simulating a typical nuclear reactor. Top flooding in thin rectangular passages can be characterized by using the span W as a characteristic length in the Wallis non-dimensional velocity. It was considered that non-uniform distributions of void fractions and velocities in the direction of circumference are important for the top flooding mechanism in annular passages, just as in top flooding in thin rectangular passages.

Key Words: top flooding, thin rectangle, annulus, passage, high aspect ratio, nuclear reactor, characteristic length, non-dimensional velocity

1. INTRODUCTION

Flooding in countercurrent gas–liquid flow is an important phenomenon in industrial applications such as heat pipes, film separators and reflux condensors. In nuclear reactor systems, flooding is very important in connection with the operation of emergency core cooling systems (ECCS). Of particular interest is the partial delivery behavior in the annular downcomer in pressurized water reactors (PWRs) under loss-of-coolant accident (LOCA) conditions. The geometry of a thin rectangular passage is very similar to that of an annular passage and also is important for water penetration between the channel boxes in boiling water reactor (BWR) LOCA. Recently, thin rectangular heat pipes have been designed to cool certain electronic devices and the flooding behavior has been studied also (Murakami *et al.* 1988).

Previous studies on flooding can be classified into two categories. One is focused on the onset of flooding and the other is focused on the partial delivery in countercurrent gas–liquid flow. In the present study, the partial delivery problem in annular and thin rectangular vertical passages was studied.

The characteristics of the partial delivery phenomenon are dependent on various parameters, such as passage geometry, fluid properties and method of operation. The end geometries play an important role in determining the partial delivery flow rate. It is believed that the water flow rate is limited at the top end of the passages in the partial delivery from the water pool above the passages, so it is called top flooding. Figure 1 shows a comparison of top flooding in passages of

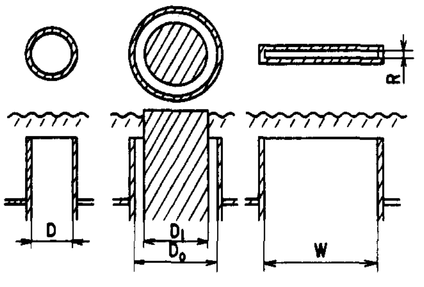

Figure 1. Top flooding in various passages.

various geometries. The gas is introduced into the lower plenum below the passage and allowed to flow upward through the passage. A pool of water in the upper plenum above the passage provides the water for penetration. In these passages, the characteristic length to describe the top flooding phenomenon should be properly defined.

It would be interesting to compare the experimental and analytical results for an annular passage simulating a reactor vessel with the data for thin rectangular passages of high aspect ratio. It was considered that the top flooding data in a thin rectangular passage would asymptotically approach those of an annular passage with increasing aspect ratio. Previous studies on top flooding in thin rectangular passages have been conducted by Mishima (1984) and Sudo *et al.* (1987). In the experiment by Mishima (1984), thin rectangular passages with gap sizes of 1.5, 2.4 and 5.0 mm and an aspect ratio of $S^* = 8$–27 were used. Sudo *et al.* (1987) used passages with gap sizes of 2.3, 5.3, 8.3 and 12.3 mm and an aspect ratio $S^* = 2.7$–29. In the present work, the test section with the larger aspect ratios $S^* = 10$–50, which are comparable to that of an annular downcomer of a representative reactor, were used and a comparison with the previous experiments for thin rectangular and annular passages was made.

2. THEORETICAL BACKGROUND FOR CHARACTERISTIC LENGTH

Previous experiments on top flooding have resulted essentially in two empirical correlations. One correlation relates the gas and liquid fluxes under the top flooding condition; Wallis (1969) proposed

$$j_G^{*1/2} + m j_L^{*1/2} = C. \qquad [1]$$

The non-dimensional velocities are defined as

$$j_i^* = \frac{\rho_i^{1/2} j_i}{[gD(\rho_L - \rho_G)]^{1/2}} \qquad (i = \mathrm{L} \text{ or } \mathrm{G}). \qquad [2]$$

where D is the characteristic length, σ is the density and g is the acceleration due to gravity. The inner diameter is taken as D in the case of round tubes. In [1], m and C are constants. Bharathan & Wallis (1983) reported that C is strongly dependent on the entrance geometry in the case of top flooding.

The other correlation deals with zero liquid penetration (Pushkina & Sorokin 1969). This theory assumes that a constant Kutateladze number (Ku) predicts the lowest gas flux for zero liquid penetration. The critical Ku is defined as

$$\mathrm{Ku} = \frac{\rho_G^{1/2} j_G}{[g\sigma(\rho_L - \rho_G)]^{1/4}} = j_G^* D^{*1/2} = 3.2, \qquad [3]$$

where σ is the surface tension, D^* is a non-dimensional characteristic length ($= D/l$) and l is the Taylor instability wavelength divided by 2π, defined as

$$l = \left[\frac{\sigma}{g(\rho_L - \rho_G)}\right]^{1/2}.$$

Ku can be obtained when the Taylor instability wavelength is used as the characteristic length in [2].

The two correlations, [1] and [3], are not consistent with each other when used to predict the top flooding condition. Equation [1] predicts geometric dependence of the gas flow rate for zero liquid penetration, while [3] does not. The experimental results show that the zero liquid penetration condition is described with j_G^* in pipes of relatively small diameter, and with Ku in pipes of relatively large diameter (Richter 1981). This means that the characteristic length in top flooding is the pipe diameter and it is limited with a multiple of the Taylor instability wavelength in large pipes.

By using liquid and gas momentum equations and a void fraction correlation at flooding in round pipes, Richter (1981) obtained

$$0.25\, D^{*6} j_G^{*6} j_L^{*2} + D^{*2} j_G^{*4} + 150 j_G^{*2} = \frac{1}{c_w}, \qquad [4]$$

where the wall friction factor is defined as $c_w = 0.008$. To obtain [4], a Wallis (1969) type interfacial shear stress correlation,

$$\tau_i = c_w\left(1 + \frac{300\delta}{D}\right)\rho_G \frac{j_G^2}{2}, \quad [5]$$

was used, where δ is the average film thickness and the void fraction ϵ was assumed nearly equal to 1. For zero liquid penetration, $j_L^* = 0$, [4] becomes

$$j_G^{*2} = -\frac{75}{D^{*2}}\left[1 - \left(1 + \frac{D^{*2}}{75^2 c_w}\right)^{1/2}\right]. \quad [6]$$

For small pipes, $D^{*2}/(75^2 c_w) < 1$, [6] can be approximated as

$$j_G^{*1/2} = \left(\frac{1}{150 c_w}\right)^{1/4} = 0.96. \quad [7]$$

For large pipes, $D^{*2}/(75^2 c_w) > 1$, [6] can be approximated as

$$j_G^* = \left(\frac{1}{D^{*2} c_w}\right)^{1/4} \quad [8]$$

or

$$\mathrm{Ku} = j_G^* D^{*1/2} = \left(\frac{1}{c_w}\right)^{1/4} = 3.3. \quad [9]$$

These relations, derived by Richter (1981), can describe successfully the experimental results for zero penetration in pipes of various diameters.

Of special interest in nuclear reactor safety is the partial delivery behavior in the downcomer of a PWR, which is in the form of an annular passage. When uniform flow behavior around the circumference is assumed and the same analytical method as used by Richter (1981) for an annular passage is employed:

$$\frac{W^{*6} J_G^{*6} J_L^{*2}}{S^{*2}} + W^{*2} J_G^{*4} + 75 J_G^{*2} S^* = \frac{1}{c_w}, \quad [10]$$

where the aspect ratio $S^* = W/R$ and non-dimensional length $W^* = W/l$. To obtain [10], the characteristic length in J^* was taken to be the average circumference W and the hydraulic diameter $2R$ was used instead of the diameter D in the interfacial shear stress correlation [5].

For zero liquid penetration,

$$J_G^{*2} = -\frac{75 S^*}{2W^{*2}}\left[1 - \left(1 + \frac{4W^{*2}}{75^2 c_w S^{*2}}\right)^{1/2}\right]. \quad [11]$$

For small gap size, $4W^{*2}/75^2 c_w S^{*2} < 1$, [11] can be approximated as

$$J_G^{*1/2} = \left(\frac{1}{75 S^* c_w}\right)^{1/4}. \quad [12]$$

Many scaled-down experiments for the downcomer of a PWR have been performed. Figure 2 shows the experimental measurements of the gas flux for zero liquid penetration in annular passages with air or steam and water as a function of the scale of the apparatus relative to a full-sized reactor vessel, as summarized by Bharathan (1979).

A representative full-sized reactor has a gap width of 0.25 m and an average circumference of 14.4 m. If the proper geometrical scaling laws to the representative reactor are used, $S^* = 57.6$ and [12] becomes

$$J_G^* = 0.17. \quad [13]$$

When the gap size is not small, J_G^* at zero liquid penetration can be calculated by [11]. The experimental data in figure 2 can be described well with the non-dimensional velocity $J_G^* = 0.16$ rather than the prediction by [11] using the physical value of air and water. According to [11], it is noteworthy that top flooding in an annular passage depends on the aspect ratio S^*. In the

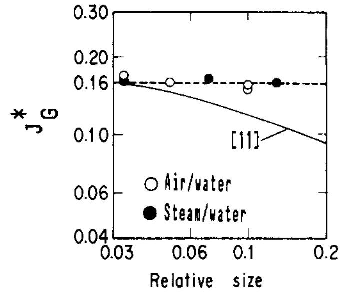

Figure 2. Non-dimensional velocity at zero penetration in an annular passage simulating a nuclear vessel, summarized by Bharathan (1979).

analysis, uniform flow around the circumference is assumed and the characteristic length in the momentum equations is the hydraulic diameter of the annuli which is equal to twice the gap size. So the aspect ratio S^* appears in the correlation when the average circumference W is adopted as the characteristic length in J_G^*.

The analytical method used by Richter (1981) successfully expresses the top flooding characteristics in pipes but does not seem to be appropriate for top flooding in annular passages. In the present paper, top flooding characteristics in annular passages are further studied by examining the top flooding behavior in thin rectangular passages of high aspect ratio.

3. EXPERIMENTAL APPARATUS AND PROCEDURE

Figure 3 is a schematic of the air–water thin rectangular test apparatus. The apparatus consists of a lower plenum, a thin rectangular passage test section and an upper plenum which are made of transparent acrylic resin for the observation of flow patterns. The test section is 1235 mm long and consists of three rectangular passages of 10 × 100, 5 × 100 and 2 × 100 mm cross section. A parametric study on the test section length was not conducted in the present study because the experimental results reported by Sudo *et al.* (1987) had shown no dependency on the test section

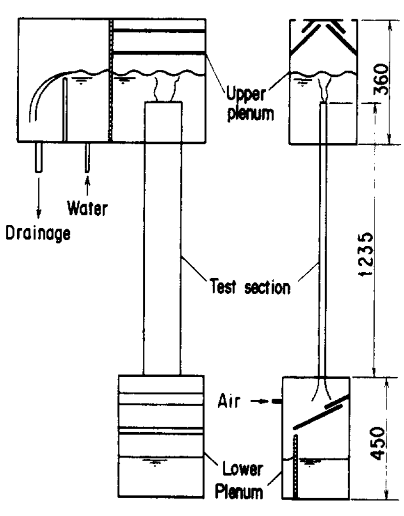

Figure 3. Thin rectangular experimental apparatus.

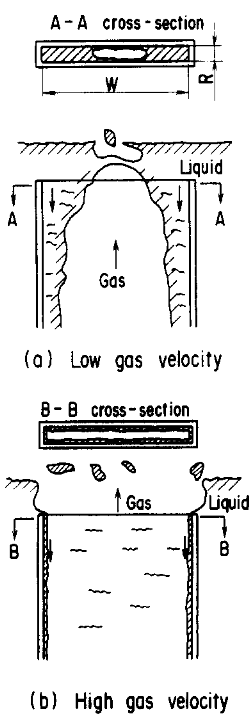

Figure 4. Typical top flooding flow patterns in a thin rectangular passage.

length for top flooding. Air was supplied to the test section from the lower plenum and discharged through the separator in the upper plenum. Water was supplied to the upper plenum and was collected at the lower plenum through the test section. The upper plenum was divided by a porous plate into two regions. One connected to a water supply and a drain, and the other connected to the protruding test section. The disturbance due to the water supply to the upper plenum of the test section was reduced by the porous plate. The lower plenum had a separator and was divided with a porous plate to measure the water level from which the falling water flow rate could be determined.

In the experiment, water was allowed to flow into the upper plenum and drain through the test section at a given air flow rate from the lower plenum. The upper plenum water level was maintained at 19, 33 and 61 mm above the top end of the test section by using three kinds of weir in the upper plenum. The downward water flow rate was obtained by noting the time interval required to accumulate a known level of water in the lower plenum.

4. EXPERIMENTAL RESULTS AND DISCUSSION

Countercurrent flow in a thin rectangular passage

Figure 4 shows typical flow patterns obtained at low and high gas velocities. At low gas velocities, the water was observed to mainly fall down at the corner part of the thin rectangular test section. At high gas velocities, a slightly thicker water film near the corner wall could be observed at the entrance of the test section and water tended to collect at the corner part during downward flow.

Figure 5 shows the experimental results for the upper plenum water levels of 19 and 61 mm. In this figure, the non-dimensional velocities j_i^* (i = L or G), defined by [2], were calculated with the characteristic length equal to twice the gap size ($2R$), which is approximately equal to the hydraulic diameter. In figure 5, the effect of the water level on the relation between j_G^* and j_L^* is small but the relation strongly depends on the gap size. This implies that the hydraulic diameter in [2] is not appropriate.

Since the void fraction and velocity distributions in the spanwise direction are considered to be important, the span W is assumed as the characteristic length in [2]. Figure 6 presents all the experimental results, replotted in terms of J_G^* and J_L^*, evaluated with the span W. The data are described well by

$$J_G^{*1/2} + 0.8\,J_L^{*1/2} = 0.58. \qquad [14]$$

Mishima (1984) conducted air–water experiments in thin rectangular channels with a span of $W = 40$ mm and gaps of 1.5, 2.4 and 5 mm. In his experiments, the water level above the top end of the test section was maintained at 300, 400 and 600 mm and the effect of the water level appeared to be small. Figure 7 shows the experimental results obtained by Mishima (1984) plotted in the same manner as in figure 6. The data are approximately described by [14].

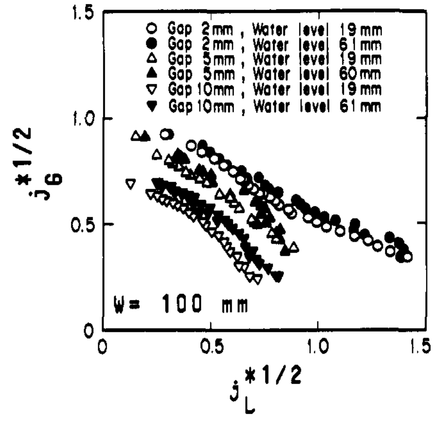

Figure 5. Experimental results in a thin rectangular passage by using the hydraulic diameter as the characteristic length in the non-dimensional velocity.

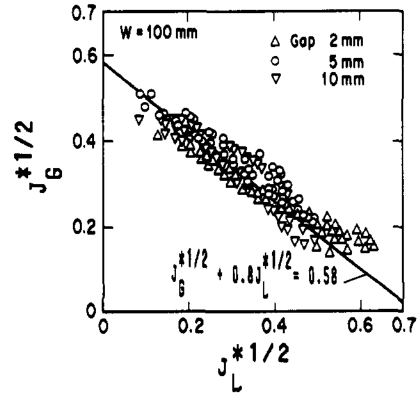

Figure 6. Experimental results in a thin rectangular passage by using the span W as the characteristic length in the non-dimensional velocity.

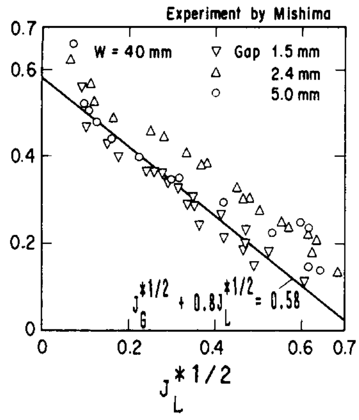

Figure 7. Experimental results for a thin rectangular passage obtained by Mishima (1984).

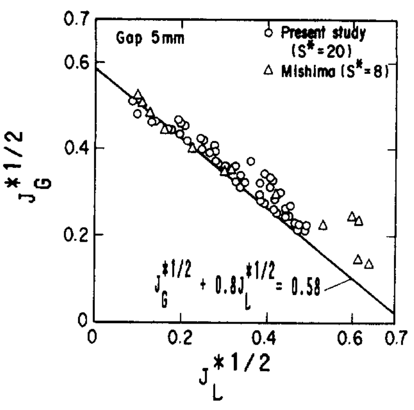

Figure 8. Comparison of the present experimental results and those of Mishima (1984) for a gap width of 5 mm.

Figure 8 shows the comparison of the present data and Mishima's (1984) data for a gap of 5 mm. The aspect ratio S^* in the present experimental apparatus was 20 and that in Mishima's apparatus was 8. Both data agree well with [14]. A non-dimensional relation for top flooding in a thin rectangular passage was therefore considered to be independent of the aspect ratio S^*. Experimental results by Sudo *et al.* (1987) also showed that value of C in [1] does not depend on the aspect ratio S^*. So the partial delivery flow rate is determined only with the span W. In thin rectangular passages, the partial delivery flow rate can be effectively reduced if the flow area is divided by walls into several "cells" in the spanwise direction.

Comparison with annular passages

Richter *et al.* (1979) conducted top flooding experiments in annular passages with o.d. = 444.5 mm and i.d. = 393.7 or 342.9 mm. The gaps and aspect ratios were 25.4 and 50.8 mm and 51.8 and 24.3, respectively. The inner wall was higher than the outer wall, as shown in figure 1. The apparatus was a 1/10 scale model of a representative full-sized reactor.

When the average circumference in Richter *et al.*'s (1979) experiment, with the span W in the present thin rectangular passage used as a characteristic length, are adopted all the experimental data can be well-correlated, as shown in figure 9. Richter *et al.*'s data for the different aspect ratios are described well by

$$J_G^{*1/2} + 0.8\,J_L^{*1/2} = 0.38. \qquad [15]$$

When the characteristic length in the annular passage is assumed to be $\frac{1}{4}$ of the average circumference, the r.h.s. of [15] becomes 0.54 and agrees approximately with [14] for the thin rectangular passage.

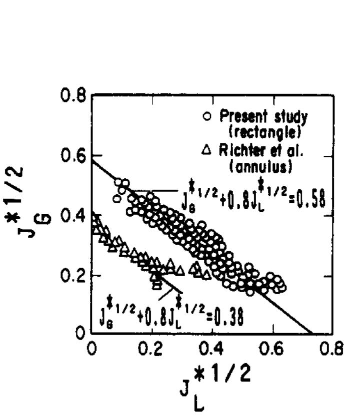

Figure 9. Experimental results in thin rectangular and annular passages.

From the zero penetration data obtained in annular passages of different scale, shown in figure 2, the r.h.s. of [15] with the average circumference becomes $(0.16)^{1/2} = 0.4$ and that with $\frac{1}{4}$ circumference becomes 0.57 and agrees well with [14]. One of the reasons for the larger value on the r.h.s. of [14] compared with [15] is thought to be the corner wall in the thin rectangular passage which enhances the phase separation and increases the downward water flow rate.

It is noteworthy that top flooding in annular passages can be characterized by using the average circumference and [11], assuming that uniform flow around the circumference does not seem to be appropriate. This suggests that the void fraction and velocity distributions in the direction of the circumference are important for the top flooding mechanism in the annular passage, just as in top flooding in a thin rectangular passage. In annular passages, there may be several "unit cells" around the circumference and therefore the characteristic length could be some fraction of the average circumference W. Non-uniform flow behavior in the annular passage has also been reported for the rising large bubbles which occupy almost the whole flow area (Griffith 1964; Barnea & Shemer 1986).

5. CONCLUSION

Top flooding experiments in thin rectangular passages with high aspect ratio were conducted to study the basic flooding characteristics and similarities with an annular passage simulating a representative nuclear reactor. The following results were obtained from the present experiments and previous experiments with annular and thin rectangular passages:

(1) Top flooding in thin rectangular passages can be characterized by using the span W as the characteristic length in the non-dimensional velocity. The span W is important for top flooding characterized by non-uniform void fraction and velocity distributions in the spanwise direction.

(2) The partial delivery flow rate strongly depend on the span W in thin rectangular passages. So the partial delivery flow rate can be effectively reduced if the flow area is divided by walls into several "cells" in the spanwise direction.

(3) Top flooding in annular passages can be characterized by using the average circumference and analysis assuming uniform flow around the circumference does not seem to be appropriate. This suggests that the non-uniform void fraction and velocity distributions in the direction of the circumference are important for the top flooding mechanism in an annular passage, just as in top flooding in thin rectangular passages. In annular passages, there may be several "unit cells" around the circumference and therefore the characteristic length could be some fraction of the average circumference W.

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