Journal of the Korean Nuclear Society
Volume 34, Number 4, pp.396 ~ 405, August, 2002

The Effect of Gap Size on Counter Current Flow Limitation Phenomena in Narrow Annular Gaps with Large Diameter

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(Receved December 14, 2001)

Abstract

An experimental study on counter-current flow limitation phenomena in narrow annular passages was carried out. The gap sizes tested were 1, 2 and 3 mm. This is very small compared with the outer diameter of the annular passage, 500 mm. It was visually observed that a CCFL might occur in some part of the periphery while the other part is remained in a counter current flow pattern. That is, non-uniform behaviour of fluids due to a 2-dimensional effect appear in a large diameter facility. Because of this non-uniformity, a CCFL is defined in the present work as the situation where net water accumulation is sustained. That is, some amount of water should not be allowed to penetrate the gap and accumulate over the gap at CCFL criterion. The measured data are presented in the form of Wallis' type correlation with characteristic length of gap size. It was found that the present correlation is in good agreement with other empirical correlation based on measurements whose test section diameter is close and the gap size is much larger than that of the present test section.

Key Words : counter current flow, CCFL, flooding, CHFG, two-phase flow, narrow annular gap, gap cooling

1. Introduction

In the TMI-2 accident, the reactor pressure vessel (RPV) received no damage and molten corium was kept inside the pressure vessel and cooled down, despite the fact that all severe accident analysis codes predicted it would fail. This suggests that there might be inherent cooling mechanisms that are not known. In order to explain the safe cool-down of the relocated corium, three cooling mechanisms have been suggested by Rempe et al. [1] and a gap-cooling mechanism is considered to be the most plausible one to have played a major role in corium cooling. In order to understand thermal-hydraulic phenomena relevant to the gap cooling mechanism CHFG (critical heat flux in gap), VISU-I & II experiments were carried out at KAERI [2]. Through these experiments, it was observed that the CCFL phenomena prevented water from wetting the heater surface and induced dryout in hemispherical narrow gap geometries. That is, CCFL determines the upper limit of the cooling capability through gaps that might be formed between relocated corium and the reactor pressure vessel. In this regard, understanding of the CCFL phenomena occurring in a narrow annular gap is believed to be essential to figuring out the dryout mechanism of relocated corium.

Counter-current flow configuration is widely used in industries such as power plants and chemical process plants using fluids to achieve their functions. This is because this flow configuration gives maximum efficiency in heat and/or mass transfer between two phases. This flow structure is not able to be preserved by the limiting phenomena known as counter-current flow limitation (CCFL) or flooding. If either liquid or gas flow is supplied more than this criterion, the flow pattern changes to a chaotic flow regime from stable counter-current flow and the fluids flow co-currently in the direction of the gas flow. In consequence, the liquid phase is not able to reach the plenum where the gas phase comes out. This phenomenon has also been of importance in the field of nuclear safety analysis [3, 4].

In previous literature, the CCFL phenomena in annular and rectangular gap geometries have been investigated in order to analyze the emergency core cooling system (ECCS) water bypass [3], direct-vessel injection (DVI) [5] and safety margin of a research reactor's rectangular fuels [6, 7, 8]. Most of analytical models and measured data on the CCFL phenomena have been presented in terms of the Wallis parameter and Kutateladze number and correlated by the following forms:

$$j_g^{*1/2} + m_w j_l^{*1/2} = C_w \tag{1}$$

$$K_g^{*1/2} + m_k K_l^{*1/2} = C_k \tag{2}$$

where,

$$j_k^* = j_k \sqrt{\frac{\rho_k}{gD(\rho_l - \rho_g)}} \ , \ K_k^* = j_k \sqrt[4]{\frac{\rho_k^2}{g\sigma(\rho_l - \rho_g)}} \tag{3}$$

The principal difference between these two dimensionless numbers is the choice of characteristic length. Wallis' parameter uses test section geometry such as diameter, gap width and span while the Kutateladze number uses Taylor wave length. Due to this fact, the Kutateladze number seems to be more adequate in describing instability-induced phenomena such as CCFL. However, Wallis' parameter is still used by many investigators. When Wallis' parameter is selected to describe CCFL models and fit their measurements, investigators have to make a decision on what length scale to use. If the geometry of the test section is far from the circular pipe, there is no general guidance for the selection. For rectangular channels, various characteristic lengths have been used depending on the authors to correlate their measurements. Sudo & Kaminaga [8] and Celata et al. [9] used the gap width, S, while Osakabe & Kawasaki [10] and Ruggles [11] used the span, W, as the characteristic length. Furthermore, Cheng [6], Mishima [12] and Mishima & Nishihara [7] suggested twice the span (2W) as the characteristic length scale. A similar situation happens with annular channels as well. Richter et al. [13], Koizumi et al. [14], Ragland et al. [15] and Lee et al. [5] used hydraulic diameter, which is the same as twice the gap size (2S) for annular passages, while Richter [16], Osakabe & Kawasaki [10] and Nakamura et al. [17] used an average circumference of the annulus as the characteristic length scale. In addition, there was a study that substitutes another characteristic length scale for the original study. Richter et al. [13] measured CCFL points using vertical annulus gap geometry whose gap size is 1 and 2 inches. They presented their measurements in terms of Wallis' parameters using hydraulic diameter (D_h = 2S) as a characteristic length scale. Later, Osakebe & Kawasaki [10] correlated Richter et al.' s measurements in terms of Wallis' parameter using average circumference (W) as a characteristic length scale to suggest the following:

$$j_g^{*1/2} + 0.8 j_l^{*1/2} = 0.38 . \quad (4)$$

It seems that the authors picked their characteristic length scale based not on physical reasoning but based on the best fit of data during the course of data regression. In the meantime, Mishima [12] derived an analytical CCFL correlation and suggested two times the gap size should be used. In the present study, gap size is used to present measurements in terms of Wallis' parameters to investigate the gap size effect.

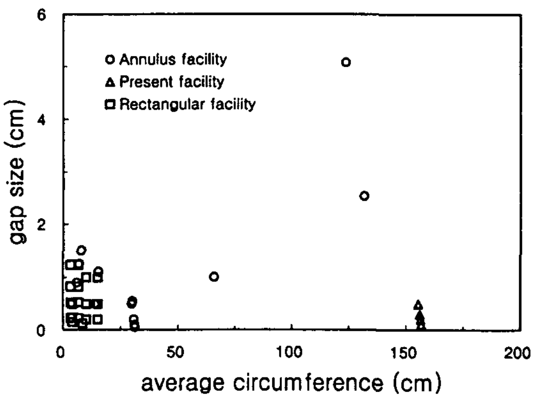


Fig. 1. Geometries of CCFL Test Facility of which Passages are Narrow Gap

The geometric scales of the experimental facilities obtained from the previous literature are compared in Fig. 1. The scale of the UPTF facility [18] which is a real nuclear reactor scale is not compared in this plot since it is much larger than the others. The average circumference stands for span of rectangular passages and the circumference of the middle between inner and outer walls of annular passages. Most previous CCFL experiments in annular passages were performed in small diameter (small average circumference) test sections. Furthermore, gap sizes of most of them were large. An outer diameter of the annular passage smaller than 10 cm and gap sizes around 10 mm are dominant in previous investigators' experiments. If a counter current flow is developed in the test sections of this size, the hydrodynamic phenomena would be quite uniform over the whole periphery while the phenomena may show a 3-D effect in actual or large size test sections.

Figure 1 also shows the geometry of the present facility. Compared with the previous experimental facility, the diameter of the present facility is large and the gap size is small. That is, the gap size to average circumference ratio of the present facility is much smaller than the previous ones. Koizumi et al. [14] carried out an experimental study on CCFL in narrow annular passages, whose objectives were similar to that of the present experiment. They measured flooding velocities in gap sizes ranging from 0.5 to 5 mm. However, the outer diameter of annular passages was 10 cm, which is much smaller than the present one. The effect of test section diameter associated with characteristic length scale in dimensionless numbers is not well understood so far. In this regard, it is necessary to carry out CCFL experiments in annular passages with a large radius of curvature and have a visual observation on what is happening in a large diameter test section. The objectives of the present experiments are to visually observe the two-phase flow behaviour inside a narrow annular gap and investigate the gap size effect on CCFL under large diameter conditions.

2. Experimental Facility

A schematic diagram of the test facility is shown in Fig. 2. The test rig consists of a test section, a water reservoir, an air buffer tank, pumps & valves, pressure transducers, thermocouples and turbine flow meters. Distilled water and air are used as working fluids. The high-pressure air coming out of the building supply line is provided to the flow control valve and turbine flow meter via an air filter and an air buffer tank whose volume is 1.3 cubic meters. The air buffer tank is used in order to damp down air pressure fluctuation and make a smooth change of air flow. The metered air is introduced to the lower plenum of the test section and goes up through a multi-holed plate (flow distributor) that is used to achieve an evenly distributed flow velocity. The water in the reservoir is forced to flow by a controllable DC pump and the flow-rate is measured by a turbine flow meter. The water is supplied to the upper part of the test section through watering holes made on the central pole. The central pole is made of stainless steel pipe of which inner diameter is 5 cm. It plays the roles of water supply line as well as alignment axis for the test section.

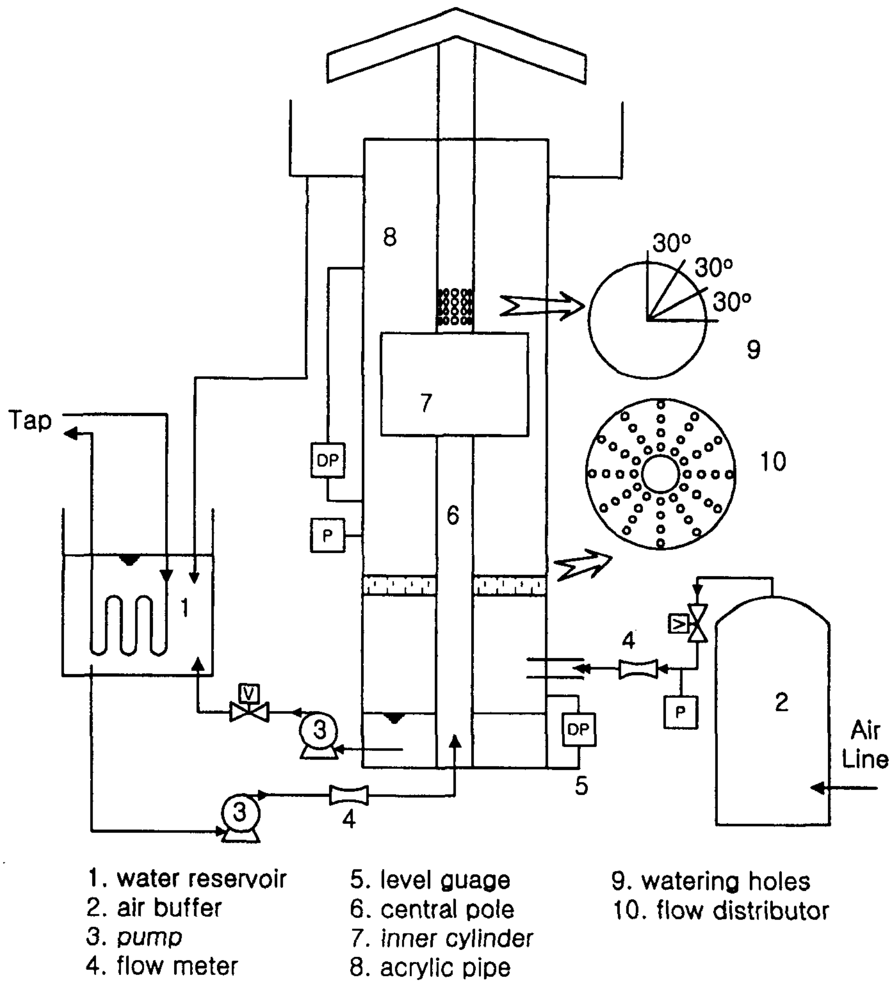


Fig. 2. Schematic Diagram of the Experimental Facility

The water coming down to the lower plenum returns to the water reservoir by a pump. The water circulates in a closed loop and the air is discharged into the atmosphere. A cooling coil is installed inside the water reservoir to maintain the water temperature at a constant level. The cooling coil gets rid of the heat generated by pumping work. Measurements are made on the differential pressure across the test section, system pressure, air-line pressure, air flow rate, and supplied water flow rates. All signals coming out of the sensors are read by an HP-VXI data acquisition system and graphically displayed on a PC-monitor as well as saved on a hard-disk.

The parts of the test section are made of acrylic resin to allow the visual observation on the two-phase flow behaviours inside the gaps. The inner diameter of the outer acrylic pipe making annular passage and the length of the inner cylinder are 500 and 250 mm, respectively. Gap sizes of 1, 2 and 3 mm are made by changing the inner cylinders which are made of acrylic resin pipe to various diameters. The sizes of the test section were chosen to be the same as the CHFG facility. This is because the geometric scaling effect was not clear until now in spite of the fact that Wallis' parameter and the Kutateladze number are used in correlating experimental CCFL data. Even though every part of test section was machined by a CNC lathe, the gap sizes were not so uniform due to manufacturing tolerance. For example, a gap size of 1 mm is too small compared with the diameter of the outer pipe of 500 mm. A manufacturing tolerance of 0.1% causes the deviation of ± 0.25 mm in the gap size, which corresponds to 25% variation for a 1 mm gap.

3. Procedures and CCFL Definition

Each run starts with a regulation of the water flow rate at a pre-determined level. The air flow-rate is step-wisely increased from nil. At each level of air flow-rate, the two-phase flow behaviour inside a gap and water accumulation in the upper plenum are observed with the naked eye. The pressure difference between the top and the bottom of a gap is monitored as well. Both air and water flow-rates are not altered and observed for more than 10 minutes. If there is no sign of water accumulation in the upper plenum, the air flow-rate is increased further. This process is repeated until there is a significant increase in the differential pressure across the gap and water starts to accumulate in the upper plenum. These two signs, water accumulation and a significant increase in the differential pressure, are used as an experimental definition of the occurrence of CCFL in the present study. This definition has been generally accepted in previous literature. Even if CCFL may locally occur in a part of the gap, the point where there is no water accumulation in the upper plenum is not considered as the CCFL. This is because such a condition does not cause a problem from the viewpoint of nuclear safety analysis. At any rate, all the supplied water penetrates gaps and reaches the lower plenum. Further details on observations are in the section below.

4. Results and Discussions

4.1. Visual Observations

Each run starts by fixing a liquid phase flow rate at a pre-determined value. Stepwise increases in the air flow rate are made from zero while the liquid flow rate is fixed at a set-value. The pressure difference between the top and the bottom of an annular gap is monitored. In addition, the behaviours of water and air inside a narrow annular gap are visually observed and the images are captured using a camera. Figure 3 shows a trace of the differential pressure for the test section whose gap size is 1 mm. The water supply is fixed at =1.152. A somewhat long trace before time zero in Fig. 3 was truncated to give a clear figure around the onset of CCFL. The trace can be divided into three regions. Region I covers up to 800 seconds in Fig. 3. A dozen step-wise increases in air flow were made before 800 seconds. Through this period, the water supplied to the upper plenum penetrates the annular gap so that no accumulation of water is observed in the upper-plenum. The pressure difference across the annular passage fluctuates within a limited range. Region II extends from the end of region I to 1200 seconds. The air flow rate increased slightly at 800 seconds. The water supplied into the upper-plenum started to accumulate. Water accumulation does not continue over a couple of minutes but penetrates the gap until no accumulated water remains in the upper-plenum. After several minutes, the water starts to accumulate again. That is, the water in the upper plenum shows cyclic behaviour of accumulation and penetration. This cyclic behaviour continues until the air flow rate increases up to just below the value of CCFL. Through this region, the pressure difference between the top and the bottom of the annular passage increases and drops in accordance with the cyclic behaviour of the water. The pressure difference increases when water accumulates and decreases when the water penetrates. However, if air flow increases just over CCFL criterion, the water accumulation continues and never shows a cyclic behaviour. This is region III. The average pressure difference continues to increase as far as the accumulation height increases in this region.

A large outer diameter test section is speculated to cause the existence of the region II. As mentioned earlier, a two-phase flow in small diameter test section may show a uniform behaviour while that in large test section does a non-uniform 3-D behaviour. Jeong & No [19] carried out CCFL experiments in circular pipes whose inner diameter is 3 cm and reported that a smooth annular flow is abruptly changed into a chaotic flow pattern at the CCFL criteria and supplied water continues to accumulate in the upper plenum. In the other hand, Glaeser [18] reported a 3-D effect on flooding phenomena in the UPTF facility.

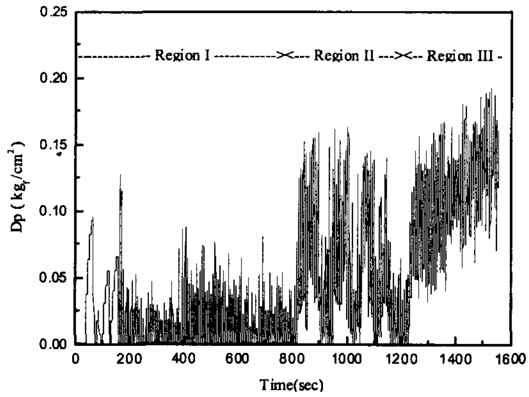
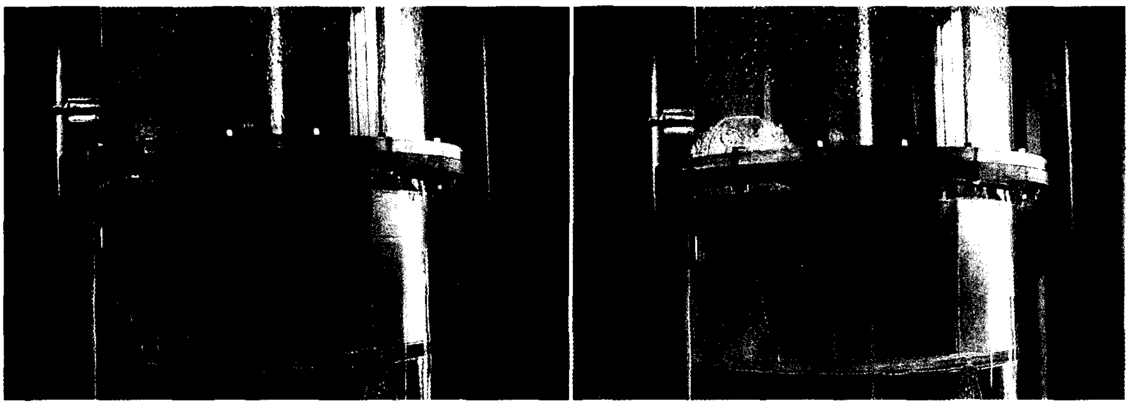


Fig. 3. Pressure Difference Between the Top and the Bottom of a 1 mm wide Annular Passage ($j_l^{*1/2}$ =1.152)

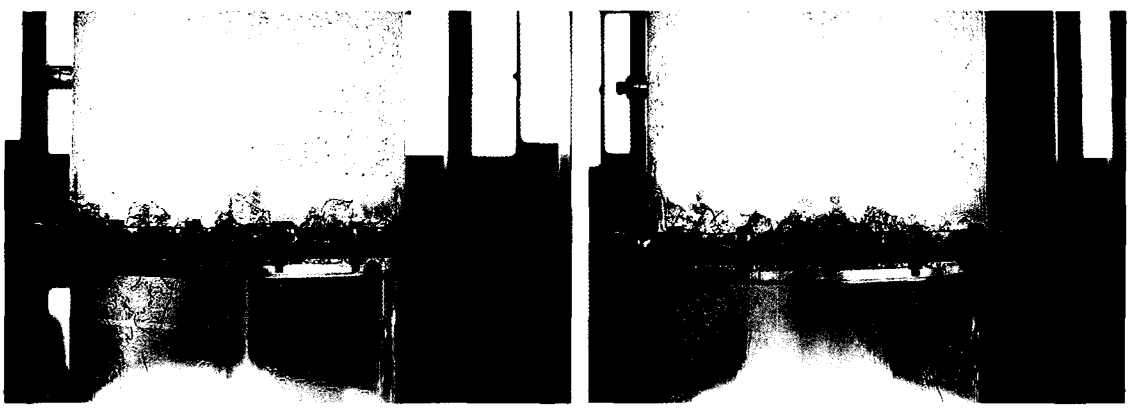
It was visually observed that the flow behaviour inside gaps is not uniform, as can be seen in Fig. 4. These photographs show typical flow behaviour in region II. When the air flow is increased up to region II, CCFL initiates at the top of the annular gap. However, the region where CCFL occurs is limited in width. That is to say, some part of the annular gap is under CCFL conditions and other parts remain at a counter-current flow pattern. This means that water is prevented from penetrating at some part of the gap while allowed to flow downwards at other parts. The CCFL limited region expands with an increase in the air flow rate. Through a set of experimental runs, it was observed that the part of the gap where CCFL initiates was always the same. The reason is believed to be the manufacturing tolerance of the rig. The parts of the test section are made of acrylic resin to allow visual observation on the two-phase flow behaviour inside gaps. The thick resin pipe was machined by a CNC lathe to make the parts of the test section. A machining tolerance of 0.1 % produces a variation of 0.25 mm in gap size for the present test section whose diameter is 500 mm. The intended gap size of 1 mm may vary from 0.75 to 1.25 mm, which corresponds to 25 % deviation. For a 2 mm gap, the deviation could be 12.5 %. It is a large deviation in comparison with the gap size of 1 mm. In spite of the fact that water can not penetrate the gap at some part of the periphery due to local CCFL, this air velocity is not defined as the CCFL gas velocity. This is because all the water supplied to the upper plenum penetrates the gap anyway and goes to the lower plenum through the other part of the gap.

If air flow rate is increased further, the flow configuration goes to region III. At this air flow rate, the whole periphery is controlled by CCFL as shown in Fig. 5(a). Sometimes, however, accumulated water penetrates through a part of the gap as shown in Fig. 5(b). This penetration lasts for a while and ends. Even though temporary penetration happens, water accumulation in the upper-plenum still continues. Based on these



(a) (b)

Fig. 4 Partially Limiting CCFL (1mm gap, $j_l^{*1/2}$=1.152)



(a) (b)

Fig. 5. Fully Limiting CCFL (1 mm gap, $j_l^{*1/2}$=1.152)

observations, the CCFL is defined in the present work as the situation where net water accumulation is sustained. It was found that the air velocities for CCFL are around 15% larger than those for the initiation of region II.

4.2. CCFL Measurements

Figure 6 show the measurements for 1, 2 and 3 mm gaps in terms of Wallis' parameter. The gap size is used as the characteristic length scale in this plot. Gap sizes of the present facility, 1, 2 and 3 mm, are less than the wavelength of Taylor instability, 17.2mm, as defined by $\lambda_T=2\pi\sqrt{\sigma/g\Delta\rho}$. The average circumference of the present facility, around 1570 mm, is much larger than the Taylor wavelength as well. The ratio of gap size to average circumference is around 0.4 ~ 2 % for the present facility. Compared with the gap size, the circumferential length is so much larger that it may be assumed to be infinite. Therefore, the average circumference may not be able to play a role of characteristic length scale. In this regard, measurements plotted in Fig. 6 are expressed in terms of Wallis' parameters with characteristic length scale of gap size.

The measurements shown in Fig. 6 are correlated in the form of Eq. (1) as follows:

$$j_g^{*1/2} + m j_l^{*1/2} = C \qquad (5)$$

where $j_k^* = j_k\sqrt{\dfrac{\rho_k}{gS(\rho_l-\rho_g)}}$.

As stated above, the gap size is used as the characteristic length scale. In order to take advantage of gap size in determining the constants m and C, a ratio of gap size to the Taylor wavelength is considered. This ratio reduces to a bond number, N_B, whose relation is as follows:

$$\frac{S}{\lambda_T} = \sqrt{\frac{S^2 g\Delta\rho}{\sigma}} = \sqrt{N_B} \ . \qquad (6)$$

The constants m and C are fitted by the least-square method as follows:

$$m = 1.431 - 0.636\ N_B^{0.463} \qquad (7)$$

$$C = 2.796 - 0.884\ N_B^{1.209} \ . \qquad (8)$$

These expressions show that the constants m and C, decrease with an increase in gap size. This empirical correlation is compared with

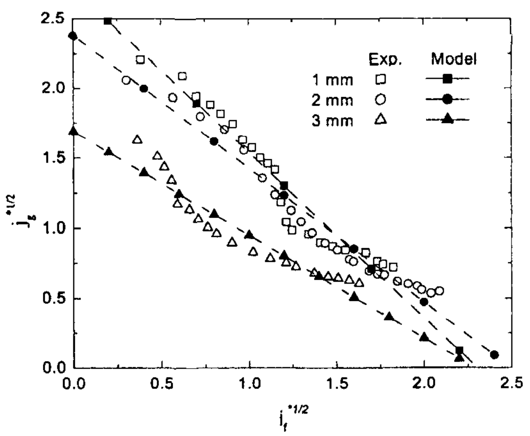


Fig. 6. Measurements and Predictions by the Empirical Eorrelation

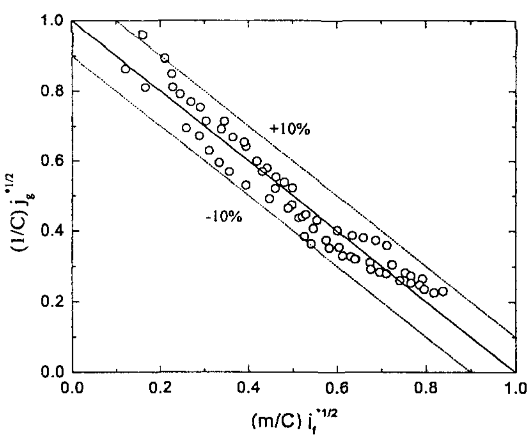


Fig. 7. CCFL Correlation for Narrow Annular Gap Geometry

measurements in Fig. 6. Another plot showing the relative discrepancy between the correlation and measurements are shown in Fig. 7. This plot shows that eqns. (5) through (8) are in good agreement with measured data within ±10% error.

Figure 8 shows the comparison between the present correlation and Osakabe & Kawasaki's correlation, eq. (4) for 1, 2 and 3 mm gaps. The axes in fig.8 represent Wallis parameters using gap size (S) as the characteristic length. In order to make this comparison plot, eq. (4) originally developed using average circumference (W) has been converted to corresponding values of which characteristic length scale is gap size. As mentioned earlier, eqn. (4) was developed based on Richter et al.'s [13] measurements. Richter et al.'s [13] test section consists of 17.5 in (44.45 cm) diametered outer pipe and 15.5 in (39.37 cm) and 13.5 in (34.29 cm) diametered inner pipes to produce 1 in (2.54 cm) and 2 in (5.08 cm) gaps. The outer diameter of the Richter et al.'s test section is close to the present one, 500 mm. In terms of gap size, however, it can be said that the present test section is much smaller than that of

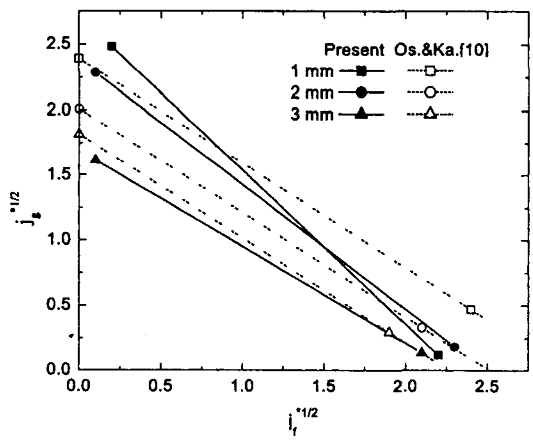


Fig. 8 Comparison Between the Present and Osakabe & Kawasaki's Correlations

Richter et al.. In spite of this discrepancy in gap size, the predictions by both of the correlations are quite close. In this regard, it can be said that aforementioned non-homogeneous two-phase flow befaviour inside gaps are properly treated by the present definition of CCFL. In addition, it seems that the present correlation can be used to predict CCFL in large range of gap size.

5. Concluding Remarks

Counter current flow limitation in narrow annular passages has been investigated. A principal difference between the present facility and the previous facilities providing annular passage is the small gap size compared with the radius of curvature. The gap sizes tested were 1, 2 and 3 mm. This is very small compared with the outer diameter of the annular passage, 500 mm. It was visually observed that a CCFL might locally occur in some part of the periphery while the other parts remain in the counter current flow pattern. In spite of the fact that water can not penetrate the gap at some part of the periphery due to local CCFL, this air velocity is not defined as the CCFL gas velocity. This is because the water supplied to the upper plenum penetrates the gap and goes to the lower plenum through the other part of the gap. Based on these observations, CCFL is defined in the present work as the situation where net water accumulation is sustained.

An empirical correlation in terms of Wallis' parameter was suggested by means of the least-squares method from the measured data. It was found that the present correlation is in good agreement with Osakabe & Kawasaki's empirical correlation which was developed based on measurements where the test section diameter is close and the gap size is much larger than the present test section.

Acknowledgements

This study has been carried out under the Nuclear R&D Program by the Korean Ministry of Science and Technology.

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