Experimental Study of Falling Water Limitation under a Counter-Current Flow in a Vertical Rectangular Channel

(1st Report, Effect of Flow Channel Configuration and Introduction of CCFL Correlation)*

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Counter-current-flow limitation (CCFL) experiments were carried out for both vertical rectangular channels and vertical circular tubes varying in size and in configuration of their cross sections to clarify CCFL characteristics in the vertical rectangular channels. Quantitative understanding of critical heat flux (CHF) in a narrow vertical rectangular channel is required for the thermohydraulic design and safety analysis of research nuclear reactors in which flat-plate-type fuel is employed. Critical heat flux under downward low velocity is closely related to falling water limitation under a counter-current flow. Experimental results showed that the equivalent hydraulic diameter d_e , i.e., the width, and gap of the channel play an important role in determining the CCFL characteristics of a rectangular channel. However, a significant influence of channel length on CCFL characteristics was not observed in the ranges investigated. Using new dimensionless parameters, the authors propose a correlation for predicting the relationship between upward air velocity and downward water velocity based on the present experimental results.

Key Words: Critical Heat Flux, Counter-Current-Flow Limitation, Flat-Plate Type Fuel, Nuclear Reactor, Vertical Rectangular Channel, Vertical Circular Tube

1. Introduction

The understanding of critical heat flux (CHF) in a narrow vertical rectangular channel is essential for core thermohydraulic design and safety analysis of research nuclear reactors in which flat-plate-type fuel is employed. It has been reported that the CHF, under such conditions as low downward velocity including the stagnant condition which would occur in anticipated operational transients and accidents, is closely related to the counter-current-flow limitation (CCFL)^{(1),(2)}, and many experiments and investigations on the CCFL have been carried out.

Wallis proposed a correlation of downward water

velocity vs upward gas velocity on the CCFL in vertical circular tubes as shown below⁽³⁾:

$$\sqrt{j_{gd}^*} + m\sqrt{j_{Ld}^*} = C \quad (1)$$

$$j_{gd}^* = j_{gd} \sqrt{\frac{\rho_g}{gd(\rho_L - \rho_g)}} \quad (2)$$

$$j_{Ld}^* = j_{Ld} \sqrt{\frac{\rho_L}{gd(\rho_L - \rho_g)}} \quad (3)$$

where m and C are constants. The m is normally unity and the C is 0.725 to 0.75 for a sharp-edged tube^{(3),(4)} and 0.875 for a round-edged tube⁽³⁾.

Richter proposed a correlation of downward water velocity vs upward gas velocity shown below, based on a theoretical analysis on CCFL for both circular and annular tubes⁽⁵⁾:

$$\left(\frac{C_w}{4}\right)Bo^3j_{gd}^{*6}j_{Ld}^{*2} + C_wBoj_{gd}^{*4} + 150C_wj_{gd}^{*2} = 1 \quad (4)$$

(for circular tubes)

$$C_wBo^3j_{gw}^{*6}\left(\frac{b}{W}\right)j_{Lw}^{*2} + C_wBoj_{gw}^{*4}$$

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$$+150C_w j_{gw}^* \left(\frac{b}{W} \right) = 1 \quad (5)$$

(for annular tubes),

where the average circumferential length W is adopted for the representative length used in the j_{gw}^* and j_{lw}^* in the case of annular tubes.

Mishima carried out the CCFL experiments for the vertical rectangular channels and investigated the effect of the size of the channel gap, b (b : the shorter-side length of the rectangular cross section)⁽²⁾. His experiments revealed that Eq.(1) could be applicable to the experimental results by adopting twice the channel width, $2a$ (a : the longer-side length of the rectangular cross section) for the representative length and 0.6 for the C in Eq.(1).

On the CCFL of emergency core cooling water injected into the PWR downcomer, Sudo investigated the constants m and C in Eq.(1) based on the results of existing experiments for annular channels and correlated the m and C with the aspect ratio b/W ⁽⁶⁾.

Sudo and Ohnuki carried out the CCFL experiments for circular tubes, investigating the effect of L/d (L : channel length, d : channel diameter) on mass velocity of water falling through the channel against the upward gas mass velocity, and revealed that the mechanism of CCFL would be different between the case of $L/d > 2$ and the case of $L/d \leq 2$ ⁽⁷⁾.

From the previous results mentioned above, it is considered that Eq.(1) is available for expressing the relationship of downward water velocity vs upward gas velocity in vertical rectangular channels. However, it has not been made clear what effects the differences in the geometrical condition of the channel (i.e., configuration of cross section, such as circular tube, annular tube and rectangular channel) have on the constants m and C in Eq.(1).

In this study, therefore, CCFL experiments were carried out for the condition of L/de (de : equivalent hydraulic diameter of rectangular channel) > 2 by changing the channel width a , the channel gap b and the channel length L in order to investigate the effect of these dimensions on the relationship of downward water velocity vs upward gas velocity. CCFL experiments were also carried out for circular tubes for investigating the differences in the characteristics of CCFL between the circular tubes and rectangular channels in this study.

This paper presents experimental results thus obtained on the CCFL characteristics for the configuration of rectangular channels.

Nomenclature

a : Channel width (longer-side length of rectangular cross section) (m)

b : Channel gap (shorter-side length of rectangular cross section) (m)

B_o : Bond number

B_o^* : Modified Bond number defined by Eq.(6)

C : Constant defined in Eq.(1)

C_w : Wall friction factor

d : Tube diameter (m)

de : Equivalent hydraulic diameter (m)

g : Acceleration of gravity (m/s^2)

j : Superficial velocity (m/s)

j^* : Dimensionless superficial velocity

L : Channel length (m)

W : Circumferential length (m)

ρ : Density (kg/m^3)

σ : Surface tension (N/m)

Subscripts

b : Based on channel gap size

d : Based on tube diameter

g : Gas phase

L : Water phase

W : Based on circumferential length

2. Experimental Apparatus and Method

A schematic diagram of the experimental apparatus for CCFL is shown in Fig. 1. The test section is composed of an upper plenum, a lower plenum and a test channel made of lucite. Air supplied by a compressor flows upwards through the test channel and is exhausted from the exit of the upper plenum into the atmosphere, while part of the water supplied continuously into the upper plenum flows downwards through the test channel and the rest of the water overflows from the upper plenum with a constant water level of 550 mm kept in the upper plenum.

The downward superficial water velocity in the test channel was calculated with a rising velocity of water level in the lower plenum. The upward superficial air velocity in the test channel was measured with rotor flow meters, correcting the effects of

Fig. 1 Schematic diagram of test section

fluid temperature and pressure.

The configuration of test channels and the experimental conditions investigated in this study are listed in Table 1.

3. Experimental Results

3.1 Downward water velocity vs upward gas velocity in circular tubes

Figure 2 shows the experimental results obtained for circular tubes in this study on the relationship of downward water velocity vs upward gas velocity. In the figure, the $\sqrt{j_{gd}^*}$ is adopted for the ordinate and the $\sqrt{j_{Ld}^*}$ for the abscissa in accordance with the expression of Wallis⁽³⁾, taking d and L as parameters. The subscript d in the dimensionless parameters, j_{gd}^* and j_{Ld}^* indicates that the tube diameter d is adopted for the representative length in j_g^* and j_L^* . Figure 2 demonstrates clearly that the experimental results for circular tubes are well represented by Eq. (1) with $C=0.7$, with no effects due to variations of the magnitude in d and L , which were investigated in this study.

As already described, it has been reported that

Table 1 Configuration of test channels and experimental conditions investigated in this study

Tube	Channel length L(mm)	250, 750
	Inner diameter d(mm)	8, 12, 20
Rectangular channel	Channel length L(mm)	72, 362, 782
	Dimension of cross section (mm)	66 x 2.3, 66 x 5.3, 66 x 8.3, 66 x 12.3, 33 x 2.3, 33 x 5.3, 33 x 8.3, 33 x 12.3
	[Width a x Gap b]	
Fluid used in this experiment		water and air
Temperature (K)		288 ~ 300
Pressure (atm)		about 1
Superficial air velocity (m/s)		1 ~ 17
Water level of upper plenum (mm)		550

Fig. 2 CCFL experimental results for circular tubes

the constant C in Eq. (1) depends on the shape of the test channel end and in such cases as sharp-edged tubes investigated in this experiment, the value of 0.725 to 0.75 has been recommended for C ^{(3),(4)}. It is, therefore, considered that the experimental results shown in Fig. 2 are well consistent with those of Wallis⁽³⁾.

3.2 Downward water velocity vs upward gas velocity in rectangular channels

Figures 3(a) and 3(b) show the experimental results obtained for rectangular channels in this study on the relationship of downward water velocity vs upward gas velocity. In the figures, $\sqrt{j_{gb}^*}$ is adopted for the ordinate and the $\sqrt{j_{Lb}^*}$ for the abscissa, taking b and L as experimental parameters. The subscript b in j_{gb}^* and j_{Lb}^* indicates the channel gap, b is adopted for the representative length in Eqs. (2) and (3) instead of tube diameter, d . Figure 3(a) shows the experimental results for $a=66$ mm and Fig. 3(b) for $a=33$ mm.

As seen clearly in Figs. 3(a) and 3(b), the smaller channel gap b gives the larger dimensionless downward water velocity j_{Lb}^* under the condition of a constant dimensionless upward gas velocity j_{gb}^* and the smaller j_{gb}^* gives the larger effect of channel gap b on j_{Lb}^* in both cases of $a=33$ and 66 mm. The effect of the magnitude in L on j_{Lb}^* is not significant in the figures.

In Figs. 3(a) and 3(b) are illustrated the values of m_b and C_b which are recommended for representing the tendencies of the experimental data for each test channel configuration, that is, each combination of a , b and L in the rectangular channel when Eq. (1) is applied to the experimental data. The subscript b in m_b and C_b indicates that the channel gap b is adopted for the representative length in j_g^* and j_L^* when Eq. (1) is applied.

The following considerations have been taken into account in determining the values of m_b and C_b in Eq. (1) for each combination of a , b and L .

i) At first, the effect of magnitude in L on j_{Lb}^* was neglected because the effect was not significant, as seen in Figs. 3(a) and 3(b). Accordingly, the experimental data which are different only in the magnitude of L can be represented by a single straight line.

ii) Next, the experimental data only with rather small j_{gb}^* and rather large j_{Lb}^* were focused on in the application of Eq. (1) to the experimental data because the effects of a and b on j_{Lb}^* are significant only for rather small j_{gb}^* and therefore, the experimental data with $\sqrt{j_{gb}^*}$ larger than about 1.2 deviate significantly from each straight line recommended for each combination of a and b in Figs. 3(a) and 3(b).

The following tendencies can be pointed out as remarkable features of the C_b and m_b thus determined in Figs. 3(a) and 3(b).

- (1) An increase of a gives an increase of both C_b and m_b .
- (2) An increase of b gives a decrease of C_b and an increase of m_b .

(a) in the case of $a=66$ mm

(b) in the case of $a=33$ mm

Fig. 3 CCFL experimental results for rectangular channels

Figures 4(a), 4(b) and 4(c) show typical flow patterns for the case of $a=66$ mm, $b=8.3$ mm and $L=782$ mm with $j_g=3.1$ m/s (in Fig. 4(a)), $j_g=8.4$ m/s (in Fig. 4(b)) and $j_g=10.1$ m/s (in Fig. 4(c)).

A wavy liquid film flow is observed on the surface along the shorter side of the cross section of the rectangular test channel in Fig. 4(a). The surface of the longer side of the cross section is wet by a thin liquid film. With an increase of j_g , dry patches appear on the surface along the longer side of the cross section, as seen in Fig. 4(b). A further increase of j_g gives an occurrence of standing waves in the liquid film flowing along the surface of the shorter side of the cross section, as seen in Fig. 4(c). At the top of the standing waves are generated the entrainments of droplets and therefore, once again, the surface along the longer side of the cross section is wet by thin liquid film. The symbols (A) to (C) in Fig. 3(a) correspond to the conditions designated by symbols (a) to (c) in Figs. 4(a) to 4(c).

In the rectangular channels, the experimental results show a significant tendency in which the downward water velocity j_L decreases asymptotically to zero with increasing upward gas velocity, j_g , while in circular tubes, the j_L decreases linearly with increasing j_g . It is considered that this is because liquid film flow exists on the surface along the shorter side of the cross section even with high enough j_g , as shown in Fig. 4(c).

Figures 5(a) and 5(b) show the comparisons among typical experimental results obtained in this study, the correlation proposed by Mishima⁽²⁾ and Eqs. (4) and (5). The experimental data for the conditions of $L=782$ mm, $a=66$ mm and $b=8.3$ mm are

(a) $j_g=3.1$ m/s (b) $j_g=8.4$ m/s (c) $j_g=10.1$ m/s

Fig. 4 Flow patterns in the vertical rectangular channels ($a=66$ mm, $b=8.3$ mm and $L=782$ mm)

shown in Fig. 5(a) and those for the conditions of $L=782$ mm, $a=66$ mm and $b=2.3$ mm in Fig. 5(b).

Figure 5(a) shows a good coincidence between the correlation proposed by Mishima⁽²⁾ and the experimental results obtained in this study but shows an apparent qualitative and quantitative discrepancy between the experimental results obtained in this study and Eq.(4) for circular tubes and Eq.(5) for annular tubes, which were both proposed by the Richter's analysis⁽⁵⁾. On the other hand, Fig. 5(b) shows that the correlation proposed by Mishima has a different tendency from that of the experimental results in this study, underestimating j_{fb}^* much more with decreasing j_{fb}^* although a rather good coincidence between the two is observed with high j_{fb}^* . This is considered to be because proper attention is not paid to the effect of channel gap b in the correlation

Fig. 5 Comparison of experimental results in this study with previous CCFL correlations

proposed by Mishima. It should be pointed out here that Eqs.(4) and (5) do not appear in the range of $\sqrt{j_{fb}^*}$ vs $\sqrt{j_{fb}^*}$ shown in Fig. 5(b).

4. Introduction of New CCFL Correlation

From the dimensional analysis, the following key dimensionless parameters other than j_{fb}^* and j_{fb}^* are introduced, which are intimately related to the CCFL in the rectangular vertical channels.

$$\left. \begin{aligned} Bo^* &= \frac{ab(\rho_L - \rho_G)g}{\sigma} \\ \frac{b}{a} \end{aligned} \right\} \quad (6)$$

The effects of dimensionless parameters Bo^* and $\frac{b}{a}$ on m_b and C_b were first investigated in Fig. 6.

Figure 6 shows the relationship of $\frac{b}{a}$ vs C_b , where C_b has already been determined in Figs. 3(a) and 3(b). The straight line illustrated in Fig. 6 represents the tendency of the experimental data and is given as below.

$$C_b = 0.66 \left(\frac{b}{a} \right)^{-0.25} \quad (7)$$

It should be noted here that no systematic effect of Bo^* on C_b appears in Fig. 6.

Figure 7 shows the relationship of Bo^* vs m_b , where m_b has already been determined in Figs. 3(a) and 3(b). The curve illustrated in Fig. 7 represents

Fig. 6 Relationship of C_b vs b/a for rectangular channels

Fig. 7 Relationship of m_b vs Bo^* for rectangular channels

Fig. 8 Experimental data arrangement with new dimensionless parameters, X_b and Y_b , for rectangular channels

the tendency of the experimental data and is given as below.

$$m_b = 0.5 + 0.0015 Bo^{*1.3} \quad (8)$$

It should also be noted here that no systematic effect of $\frac{b}{a}$ on m_b appears.

In order to correlate well the relationship of j_{fb}^* vs j_{lb}^* using m_b and C_b , the following two dimensionless parameters were introduced in this study.

$$X_b = \left(\frac{m_b}{C_b} \right) \sqrt{j_{lb}^*} \quad (9)$$

$$Y_b = \left(\frac{1}{C_b} \right) \sqrt{j_{fb}^*} \quad (10)$$

From Eqs. (6) and (7), the X_b and Y_b can be rewritten as follows :

$$X_b = 1.52 \left(\frac{b}{a} \right)^{0.25} (0.5 + 0.0015 Bo^{*1.3}) \sqrt{j_{lb}^*} \quad (11)$$

$$Y_b = 1.52 \left(\frac{b}{a} \right)^{0.25} \sqrt{j_{fb}^*} \quad (12)$$

Taking these two dimensionless parameters, X_b and Y_b , for the abscissa and the ordinate, respectively, Fig. 8 shows all of the experimental data obtained for the rectangular channels in this study. The solid curve illustrated in Fig. 8 best represents the tendency of the experimental data and is given as follows.

$$Y_b = 1.3 \exp(-2.1 X_b) \quad (13)$$

Equation (13) can predict the experimental data well with the error of $\pm 15\%$ for the CCFL experimental data obtained in this study by using the dimensionless parameters, X_b and Y_b , as shown in Fig. 8.

5. Conclusions

In this study, the CCFL experiments were carried out by systematically varying the magnitude in tube diameter d and tube length L of the vertical circular tubes, and in channel width a , channel gap b and channel length L of vertical rectangular channels. As a result, the following conclusions were obtained.

(1) The tendency of the experimental data for vertical circular tubes is well represented by Eq. (1).

(2) An increase of channel gap b gives a significant decrease in $\sqrt{j_{fb}^*}$ under the condition of the same $\sqrt{j_{lb}^*}$ in the case of vertical rectangular channels, while no significant effect of channel length L was observed in this study for the vertical rectangular channel.

(3) In the vertical rectangular channels, it was observed that the $\sqrt{j_{fb}^*}$ tends to decrease asymptotically to zero with increasing $\sqrt{j_{lb}^*}$ because there exists liquid film flowing on the surface along the shorter-side of the cross section even under the condition of high gas velocity.

(4) The CCFL experimental data for vertical rectangular channels can be predicted within the error of $\pm 15\%$ by Eq. (13), in which the channel width a , the channel gap b , the dimensionless parameter Bo^* and the aspect ratio $\frac{b}{a}$ are included as major parameters representing the effects of the configuration of rectangular channels.

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