Phase Distribution for Air-water Two-phase Flow in Annuli[†]By Tohru FURUKAWA^{††} and Kotohiko SEKOGUCHI^{†††}

Experimental data are presented on the phase distribution of air-water two-phase mixtures which flow vertically upwards in annular passages. Three annuli with different radius ratios, $R_1/R_2=5/13$, $8/13$ and $10/13$, are used in the present experiments.

Flow patterns observed in the annuli are first demonstrated. Next, two items characterizing void fraction distributions, i.e. void fraction near the wall and the position of the radius of maximum void fraction are discussed with attention paid to the effect of the passage width. Flow regimes concerned herein cover bubbly, slug, froth and froth-annular or huge wave flow. Finally, an attempt is made to obtain a correlation for evaluating cross-sectional average void fraction. The proposed correlation is in good agreement with experimental values for both the annuli and a round tube.

Key Words : Multiphase Flow, Thermal Engineering, Flow Pattern, Void Fraction, Phase Distribution

1. Introduction

Steam generators used widely in nuclear reactors hold a number of vertical evaporator tubes within various shapes and dimensions of containers such as channel boxes, pressure tubes or pressure vessels. Water flows in the subchannels, formed between neighboring evaporator tubes or tubes and their container wall, together with steam generating on the tubes. Cross-sectional configurations of the subchannels are classified into two basic types in combination of convex surfaces, as tubes, and a convex surface and a concave surface, as a corner of tube container. The effect of such different configurations of subchannels on two-phase flow characteristics remains yet unknown. Experiments on critical heat flux in rod bundles⁽¹⁾ revealed that hot spots appear on the heated tube surfaces facing either the narrow gaps or the smaller areas of subchannels. This fact implies a maldistribution of the two-phase mixtures around a tube.

An annular flow passage formed by a pair of concentric tubes is one of the simplest configurations of subchannels. However, knowledge on the two-phase flow characteristics in annular passages is not yet sufficient compared with that on those in circular tubes. This paper presents experimental results on lateral phase distribution, flow patterns, and cross-sectional averaged void fraction in three different sizes of annular flow passages, i.e. three inside tubes to one outer tube, as well as in a circular tube.

2. Nomenclature

D : Inner diameter of tube, m
 Dh : Hydraulic diameter $2(R_2-R_1)$, m
 DeU : Tube diameter defined by equation (8), m
 dvs : Equivalent bubble diameter defined by equation (1), mm
 g : Acceleration of gravity, m/s^2
 $\bar{j}$: Superficial velocity, m/s
 R : Radius of tube, m
 r : Distance measured from the channel center, m
 Ue : Modified wetted perimeter defined by equation (6), m
 u : Velocity, m/s
 y : Distance measured from the wall, m
 α : Void fraction
 β : Volume flow quality

Subscripts

a : Position of maximum value of the void fraction distribution
 g : Gas phase
 l : Liquid phase
 1 : Inner surface of the annulus or the portion between r_a and the inner tube
 2 : Outer surface of the annulus or the portion between r_a and the outer tube
 cal : Calculated value
 exp : Experimental value

Superscript

[^] : Averaged value across flow

3. Experiments

3.1 Experimental apparatus

Figures 1(a) and (b) show a schematic diagram of the experimental apparatus and dimensions of test tubes used, respectively. The experiments were carried out in three vertical concentric annuli with a total length of about 2.4 m. The annular passage widths were 3, 5, and 8 mm for a 26.0 mm inner diameter tube as the outer

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tube. Hereafter, these passages are written as A-3, A-5, and A-8. The outer tube was made of acrylic resin to observe flow patterns, and the inner tubes were made of stainless steel. The inner tubes were centered by means of three radial spacer pins each 0.5 or 0.6 m in axial length. Each spacer pin made of stainless steel was 2.0 mm in dia. and hemispherical at point of contact with the inner tubes. A round tube (briefly written as Rt) of 26.0 mm in dia. and about 4.9 m long was also used in the present experiments to compare with the results obtained from the experiments of annuli. Air-water mixtures formed in an air-water mixer ⑪ flowed vertically upwards through the annuli or the round tube, and were finally separated into individual phases by a separator ⑫. The water was diverted back to a water storage tank ①. A measuring section was located at about $L_2=2.4$ m downstream of the air-water mixer for the annuli ($L_2/D_h \approx 233:(A-3)$, $140:(A-5)$, $87.5:(A-8)$) and at about $L_2=3.0$ m for the round tube ($L_2/D_h \approx 115$). Void fraction and passage frequency of bubbles were measured at the section, near which flow pattern was also observed. The air-water mixer had such construction that air flowed radially into water through 60 holes (2.0 mm dia.) drilled at the outer tube. These holes consisted of 12 holes per row on the periphery and 5 rows (5 mm spacing of the rows) in triangular array.

3.2 Instrumentation

The results obtained by visual observation of flow patterns were compared with those by a quantitative method. Equivalent diameter, d_{vs} , determined from void volume and gas-liquid interfacial area was used as a scale of quantitative discrimination. The definition of d_{vs} is given by⁽²⁾

$$d_{vs} = 1500 \alpha_{up} / fp \quad (1)$$

where α is the local void fraction and fp

Fig.1(a) Schematic diagram of experimental apparatus

the passage frequency of gas-liquid interface at the middle point of the passage width for the annuli and at the tube center for the round tube, and u_p is taken as the sum of superficial air and water velocities. The radial distribution of void fractions was obtained using a traversable l-type conductance probe. The probe was made of platinum wire with 0.2 mm in dia., and its tip was sharpened like a needle. The surface of the probe was electrically insulated by coating with a thin resin film except the needle tip used as an electrode. Then, the corresponding fixed electrode was the inner metal tube surface for the annuli and a brass rod (8.0 mm dia.) mounted flush with the inner wall surface for the round tube. The radial distance from the fixed electrodes to the needle electrode, which was inserted through the outer tube, was measured by a micrometer with an accuracy of $\pm 10^{-3}$ mm. The needle probe was traversed from $y_1=0.1$ mm, a distance from the outer wall surface of the inner tube, to $y_2=0.3$ mm, a distance from the inner wall surface of the outer tube, for the annuli; and from $y=0.5$ to 15 mm (tube center: $y=13$ mm) for the round tube. Measuring intervals were selected narrower in the vicinity of the wall but broader in the central core.

Cross-sectional average void fraction $\hat{\alpha}$ was obtained by integrating the local void fraction α over the cross section. For comparison, volume average void fraction $\langle \alpha \rangle$ in the round tube was measured by the method of simultaneous quick closing cocks for representative test runs belonging to bubbly, slug and froth regimes. $\langle \alpha \rangle$ was the ratio of air volume trapped between the quick closing cocks to the total volume whose axial length was 1.6 m. The measuring section of the local void fraction was located at about the middle point between the cocks. The quick closing operation was repeated fifteen times in a test run, and the arithmetical average was taken as the value of $\langle \alpha \rangle$. Values of $\hat{\alpha}/\langle \alpha \rangle$ fell into a range from 0.968 to 1.013 under the same flow condition. Consequently, it can be considered that $\hat{\alpha}$ was nearly equal to $\langle \alpha \rangle$. The flow condition for testing were as follows: pressure: 102 $\sim$ 159 kPa, water temperature: 33°C, superficial air velocity, j_g : 0.2 $\sim$ 2.0 m/s, superficial water velocity, j_l : 0.1 $\sim$ 2.0 m/s.

Fig.1(b) Dimensions of test channels

4. Experimental Results and Discussion

4.1 Flow pattern

In conformity to the discrimination of flow patterns in a round tube, the flow patterns in an annular passage were classified into bubbly, slug, froth, and annular flows. Examples of photograph for these flow patterns are shown in Fig.2, which gives comparison between those in the annulus A-5 and the round tube. The features of flow patterns observed in the annuli are as follows. Bubbly flow (designated as B): The gas phase is dispersed in a form of discrete bubbles in the continuous liquid phase, and the flow configuration is essentially similar to that in the round tube. Slug flow (S): Gas-liquid interface of a gas slug is relatively smooth, but circumferentially not uniform. All gas slugs are not ring-shaped. They move upwards partly coiling around the inner tube. Froth flow (F): Large gas slugs present a very rough interface. In contrast to the slug flow mentioned above, most gas slugs are ring-shaped. Many small bubbles of 1 mm or less in diameter are contained in liquid slug and also in liquid film around gas slug at higher superficial liquid velocities, say, greater than 1 m/s. Annular flow (A): Liquid travels on the inner and outer tube walls in the form of films while gas occupies the central core. Liquid film in both the annuli and round tube are similar in configuration and behavior of the gas-liquid interfaces. Figure 3 shows the flow pattern maps obtained on the basis of the specific values of equivalent bubble diameter, d_{vs} , which are 6 mm and 200 mm for the flow pattern transitions (thick lines) from bubbly to slug or froth flow and froth to annular flow. These values of

Fig.2 Examples of photographs of air-water flow in annulus(A-5) and in round tube

Fig.3 Flow maps for each channel

d_{vs} were decided from visual observations made using the annulus A-5, a round tube and a duct consisting of two subchannels.⁽²⁾ In Fig.3, thin lines denote the lines with constant values of $\hat{\alpha}$ which were drawn to examine the relevance between $\hat{\alpha}$ -values and flow patterns. Solid, broken, dotted and chain lines correspond to the results of the passages A-3, A-5, A-8 and Rt, respectively. Flow pattern transition lines for A-3 and A-8 discriminated by visual observation though not drawn in this figure were in fairly good agreement with those drawn from the values of d_{vs} .

The figure indicates that the lines of $d_{vs}=6$ mm for the individual channels lie as close to each other as those of $d_{vs}=200$ mm for the annuli do. This fact also suggests that the location of d_{vs} -constant lines is not much influenced by the passage width. But in the case of the round tube, froth-annular transition occurs at lower air velocity than that in the annuli does. Referring to $\hat{\alpha}$ for each channel, $\hat{\alpha}=0.2\sim0.3$ corresponds to $d_{vs}=6$ mm and $\hat{\alpha}=0.7\sim0.8$ to $d_{vs}=200$ mm. The value of $\hat{\alpha}$ under the same flow condition decreases as the passage width becomes narrow.

4.2 Void fraction distribution (VFD) in cross-section

Figure 4 shows the VFD in cross-section in annuli and the round tube for various combinations of j_g and j_l . The axis of abscissa is distance, r , from the tube center. The outer wall surface of the inner tube for each annulus corresponds to $r=5$ (A-8), 8 (A-5), and 10 mm(A-3), and the inner wall surface of the outer tube or the round tube corresponds to $r=13$ mm. In Fig.4, there can be seen the dominant characteristics for the VFD in the annuli as follows: (1) Void fraction near the wall under the

same flow condition decreases as the passage width becomes larger, but on the contrary the maximum value of VFD increases as it becomes larger and (2) the VFD profile is unsymmetric about the point of maximum void fraction, and the location of maximum peak point comes nearer to the inner tube side than to the outer tube side. Discussion regarding these characteristics is made below.

Fig.4 Radial void fraction distributions

4.2.1 Void fraction near the wall surface

Figure 5 shows the VFD near the inner and outer wall surfaces. The logarithmic scale of distance from each wall surface is taken to show in detail the VFD near the wall. As shown in Fig.5, void fraction near the inner wall surface (marked by open symbols) increases with the passage width as a whole. Such trend is also seen near the outer wall surface (marked by solid symbols). Void fraction near the inner wall surface becomes larger than

that near the outer wall surface. Figure 6 compares α_1 and α_2 which are local void fractions at the points of $y=0.5$ mm from the inner and outer wall surfaces. From this figure, it is seen that the difference between α_1 and α_2 increases with the passage width and j_L .

In Fig.5, the void fraction near the wall for the round tube takes still smaller value than that near the outer wall surface for A-8. The difference between

Fig.5 Void fraction distributions near the wall

Fig.6 Relationship between α^+ and j_l for each channel

them is the most remarkable for slug flow or slug-froth transitional region (SF), and becomes smaller as flow pattern changes to bubbly or annular flow. Value of, y , indicated by an arrow represents the experimental value of minimum film thickness, tf_{min} , which was obtained by authors in previous work.⁽³⁾ These values were measured using the constant current method. The arrows of solid and broken lines show tf_{min} on the wall of the round tube with 26.0 mm inner diameter and on the outer wall of the inner tube in annulus, respectively. The dimension of this annulus is nearly equal A-5 (marked by $\circ$) in the present experiments. As shown in this figure, tf_{min} predicted by extrapolating the VFD curve to a value of $\alpha \approx 0$ is in approximate agreement with tf_{min} indicated by the arrows. From the comparison

Fig.7 Void fraction profiles in the annulus of A-5

between tf_{min} in the annulus and that in the tube, it is found that tf_{min} decreases with an increasing void fraction near the wall.

As the consequence of comparison of void fraction near the wall for each channel mentioned above, it is inferred that tf_{min} decreases as the passage width becomes narrow, and that tf_{min} on the inner tube wall becomes smaller than that on the outer tube wall.

4.2.2 Position of the radius of maximum void fraction

Figure 7 shows an example of VFDs for A-5. The position of the radius of maximum void fraction is denoted by $y_{1a}^+ = (r_a - R_1) / (R_2 - R_1)$, where r_a is the radial distance from tube center to the maximum VFD. From this figure, it is clearly found that y_{1a}^+ lies to the inner tube side, and draws still nearer to the inner tube surface with an increasing, j_l . The same trend as this can be seen in other channels, A-3 and A-8. Figure 8 indicates the effects of the passage width and j_g on y_{1a}^+ under $j_l = 1.0$ m/s. Values of y_{1a}^+ fluctuate a little with an increasing j_g ,

Fig.8 Position of the radius of maximum void fraction

y_{1a}^+ : dimensionless distance of the radius of maximum void fraction

$\bar{y}_{1a}^+$: mean value of y_{1a}^+ except for the case of bubbly flow

y_{1v}^+ : dimensionless distance of the radius of maximum water velocity for the flow of water phase alone

but j_L has not such an effect on y_{1a}^+ as j_L . Thick solid (A-3), broken (A-5) and chain lines (A-8) represent $\bar{y}_{1a}^+$ which denotes the mean values of y_{1a}^+ for the experimental points except that for bubbly flow region. From this figure, it is found that the wider the passage, the smaller becomes $\bar{y}_{1a}^+$. The same tendency can be seen also in the results examined for other water velocities as shown in Table 1. In addition, the aforementioned trend that $\bar{y}_{1a}^+$ decreases with an increasing j_L can be seen also for A-3 and A-8 as well as A-5. The position of the radius of maximum velocity y_{1v}^+ for the flow of water phase alone is also located at the inner tube side like that of $\bar{y}_{1a}^+$ as shown in Fig. 8. The value of y_{1v}^+ was obtained by using the empirical correlation of

Table 1 Values of $\bar{y}_{1a}^+$ for each superficial water velocity

j_L , m/s	0.2	0.5	1.0	2.0
A-3	0.483	0.403	0.384	0.350
A-5	0.422	0.384	0.373	0.350
A-8	0.374	0.360	0.345	0.290

Rothfus et al.⁽⁴⁾ which was in good agreement with the experimental values at high Reynolds numbers. Similarly to $\bar{y}_{1a}^+$, y_{1v}^+ draws nearer to the inner tube with an increasing passage width. However, $\bar{y}_{1a}^+$ lies still closer to the inner tube than y_{1v}^+ does.

Figure 9 indicates comparison between $\hat{\alpha}_1$ and $\hat{\alpha}_2$ which were measured for each annulus: $\hat{\alpha}_1$ and $\hat{\alpha}_2$ denote the cross-sectional average void fraction at the portion between r_a and the inner tube wall, and between r_a and the outer tube wall, respectively. As shown in this figure, $\hat{\alpha}_1$ becomes larger than $\hat{\alpha}_2$ except in a few cases of low water velocity, $j_L=0.2$ m/s. The difference between $\hat{\alpha}_1$ or $\hat{\alpha}_2$ and $\hat{\alpha}$, which means overall cross-sectional average void fraction in channel, is nearly $(\hat{\alpha}_1-\hat{\alpha})=0.029$ and $(\hat{\alpha}-\hat{\alpha}_2)=0.013$, regardless of the passage width and the flow conditions. Accordingly, it is possible to assume that $\hat{\alpha}_1$ or $\hat{\alpha}_2$ is nearly equal to $\hat{\alpha}$.

4.3 Cross-sectional average void fraction

In this section, an attempt is made to derive a correlation for evaluating the cross-sectional average void fraction $\hat{\alpha}$. Figures 10(a) and (b) show comparison of calculated ($\hat{\alpha}_{cal}$) and experimental values ($\hat{\alpha}_{exp}$). $\hat{\alpha}_{cal}$ in Fig. 10(a) was obtained from the following equation.

$$\hat{\alpha}_{cal}=j_g/u_g \quad (2)$$

where u_g is the rising velocity of gas slug, and given by Nicklin's equation below.⁽⁵⁾

$$u_g=1.2(j_g+j_L)+0.35\sqrt{gD} \quad (3)$$

where D denotes the hydraulic diameter $D_h=2(R_2-R_1)$ for the annuli, and the inner diameter for the round tube. As shown in Fig. 10(a), for $\hat{\alpha}_{exp}<0.75$, $\hat{\alpha}_{cal}$ is in good agreement with $\hat{\alpha}_{exp}$ for the round tube, but for the annuli, the agreement of both values becomes worse with a decreasing passage width. This suggests that u_g calculated from equation (3) differs from the actual u_g . Griffith measured the rising velocity of a single gas slug, u_{go} , in stationary liquid using annuli with three

Fig. 9 Comparison of $\hat{\alpha}_1$ and $\hat{\alpha}_2$ for each channel

$\hat{\alpha}_1$, $\hat{\alpha}_2$: cross-sectional average void fractions at the portion between r_a and the inner tube, and between r_a and the outer tube, respectively

Fig. 10 Comparison between calculated and experimental values of $\hat{\alpha}$

different passage widths.⁽⁶⁾ As a result, Griffith has reported that u_{g0} increases with a decreasing passage width. Therefore, it is contrary to this result to use D_h in equation (3). So it is assumed that u_g may be calculated from the following equation in consideration of representative dimension of channel.

$$u_g = K_1(j_g + j_l) + K_2\sqrt{gDeU} \quad (4)$$

Using the relation of $\hat{\alpha} = j_g/u_g$, equation (4) becomes

$$\frac{j_g}{\hat{\alpha}\sqrt{gDeU}} = K_1\left(\frac{j_g + j_l}{\sqrt{gDeU}}\right) + K_2 \quad (5)$$

where DeU is a tube diameter with peripheral length equivalent to modified wetted perimeter as stated below, and is determined as follows. The modified wetted perimeter U_e is assumed to be expressed by

$$U_e = 2\pi R_2 + 2\pi R_1 \{R_2/(R_2 - R_1)\}^n \quad (6)$$

where $\{R_2/(R_2 - R_1)\}^n$ denotes the modified term, and exponent, n , is determined by means of a trial and error method until experimental values of tube friction factor λ in a single phase flow of water obtained by using the modified hydraulic diameter $De_m = 4\pi(R_2^2 - R_1^2)/U_e$ as representative dimension become nearly equal to λ obtained from Blasius equation by using De_m . As a result, n is obtained by

$$n = (R_2 - R_1)/R_2 \quad (7)$$

Therefore, from equations (6) and (7), DeU is given by

$$DeU = U_e/\pi = 2R_2 + 2R_1\psi^{1/\psi} \quad (8)$$

where $\psi = R_2/(R_2 - R_1)$. Value of DeU becomes a little larger than equivalent-peripheral diameter De reported by Sato et al.⁽⁷⁾ De is used to correlate the rising velocity of the gas slug in various non-circular channels. On the other hand, DeU is restricted to the annuli and the round tube. DeU , however, is used to correlate not only the rising velocity of the gas slug but also the frictional pressure losses. Namely, in employing Lockhart-Martinelli method to correlate the experimental values of frictional pressure losses by using the modified hydraulic diameter $De_m = 4(R_2^2 - R_1^2)/DeU$, it was made sure that the experimental points for the annuli and the round tube were in good agreement with the curve of Lockhart-Martinelli.⁽⁸⁾ Each friction factor, supposing that gas or liquid phase flows alone in the channel, was determined from Blasius equation by using De_m .

The constants K_1 and K_2 in equation (5) are obtained by using the least square method for $\hat{\alpha}_{exp} \leq 0.75$. As a result, K_1 and K_2 become 1.28 and 0.35 for the annuli and the round tube. For $\hat{\alpha}_{exp} \leq 0.75$, it was made certain that $\hat{\alpha}_{cal}$ calculated using equations (2) and (4) was in good agreement with $\hat{\alpha}_{exp}$. For $\hat{\alpha}_{exp} > 0.75$, however, the agreement of both values was poor.

This trend was also reported by Sadatomi et al.⁽⁹⁾

Next, an attempt was made to derive an empirical correlation that could also correlate $\hat{\alpha}_{exp}$ for high void fraction region ($\hat{\alpha}_{exp} > 0.75$). It is assumed that the correlation of $\hat{\alpha}$ has a form of the following equation.

$$\frac{j_g}{\hat{\alpha}\sqrt{gDeU}} = K_3 \left(\frac{j_g + j_l}{\sqrt{gDeU}} \right)^m \quad (9)$$

where the constant K_3 and the exponent, m , are 1.623 and 0.882, respectively, which were determined using the least square method for $\hat{\alpha}_{exp}$ in the annuli and the round tube. Substituting these values into equation (9), $\hat{\alpha}$ is expressed by

$$\hat{\alpha} = 0.616\beta \left(\frac{j_g + j_l}{\sqrt{gDeU}} \right)^{0.118} \quad (10)$$

where $\beta = j_g/(j_g + j_l)$. Comparison between $\hat{\alpha}_{cal}$ obtained from the equation (10) and $\hat{\alpha}_{exp}$ is made in Fig.10(b). The agreement is good. Figure 11 shows comparison between the calculated values $(\hat{\alpha}/(1-\hat{\alpha}))_{cal}$ obtained from the correlation of authors, Inoue et al.⁽¹⁰⁾ and Katsuhara et al.⁽¹¹⁾ and experimental values $(\hat{\alpha}/(1-\hat{\alpha}))_{exp}$. Values of standard deviation σ given by the following equation are given in Table 2 in

Fig.11 Comparison of correlation with experimental values of $\hat{\alpha}$

order to examine the scatter of $\hat{\alpha}_{\text{exp}}$ to $\hat{\alpha}_{\text{cal}}$.

$$\sigma = \sqrt{\frac{1}{N} \sum (\hat{\alpha}_{\text{exp}} - \hat{\alpha}_{\text{cal}})^2} \quad (11)$$

where N is number of experimental points. In this table, values of σ for the correlations of Lockhart & Martinelli,⁽⁸⁾ Smith,⁽¹²⁾ and Baroczy⁽¹³⁾ are also listed. Judging from the results of Fig. 11 and values of σ , the correlation of authors shows better agreement than the other ones.

Table 2 Standard deviation of experimental values from predicted values of $\hat{\alpha}$

	A - 3	A - 5	A - 8	Rt
①	0.0745	0.0675	0.0554	0.0653
②	0.0361	0.0411	0.0511	0.0448
③	0.0878	0.0734	0.0490	0.0758
④	0.0653	0.0642	0.0951	0.0878
⑤	0.0419	0.0504	0.0843	0.0850
⑥	0.0317	0.0361	0.0478	0.0372

①: Inoue *et al.*⁽¹⁰⁾, ②: Katsuhara *et al.*⁽¹¹⁾
 ③: Smith⁽¹²⁾, ④: Baroczy⁽¹³⁾
 ⑤: Lockhart & Martinelli⁽⁸⁾, ⑥: Authors

5. Conclusions

An experimental study was made to reveal the characteristic of the phase distribution in three annuli which differed in the passage width. Further, an attempt was made to obtain a correlation for evaluating for cross-sectional average void fraction. The results are summarized as follows:

- (1) Void fraction near the inner and outer wall surfaces increases with a decreasing passage width under same flow conditions.
- (2) Void fraction near the inner tube wall surface is larger than that near the outer wall surface, and the difference between the former and the latter becomes larger as the passage width and the water flow velocity increase.
- (3) The position of the radius of maximum void fraction lies closer to the inner tube wall than to the outer tube wall, and its position draws nearer to the inner tube wall with an increasing passage width and water flow velocity.
- (4) Comparing $\hat{\alpha}_1$ (for the portion between the radius of maximum void fraction and the inner wall) with $\hat{\alpha}_2$ (for the portion between the radius of maximum

void fraction and the outer wall), the former is larger than the latter as a whole. However, the difference between the two values is small. Therefore, it can be considered that $\hat{\alpha}_1$ or $\hat{\alpha}_2$ is equal to $\hat{\alpha}$ (for overall cross-section in an annulus).

- (5) A correlation, i.e., equation (10) for evaluating cross-sectional average void fraction was obtained. As representative dimension of channel used herein, a tube diameter with peripheral length equivalent to the modified wetted perimeter was employed.

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References

- (1) Takatasu, M., et al., Report No. 12, JUICE Meeting on Reactor Heat Transfer and Hydrodynamics for Heavy Water Reactor, (1974-9), p. 1.
- (2) Sekoguchi, K., et al., Proc. 15th Symp. Heat Transf. (in Japanese), 1978, p. 361.
- (3) Sekoguchi, K., et al., Trans. Japan Soc. Mech. Engrs. (in Japanese), Vol. 46, No. 407(1978-7), p. 1295.
- (4) Rothfus, R. I., et al., A.I.Ch.E.J., Vol. 12, No. 6(1966), p. 1086.
- (5) Nicklin, D. J., et al., Trans. Instn. Chem. Engrs., Vol. 40, No. 1(1962), p. 61.
- (6) Griffith, P., Trans. ASME. Ser. C, Vol. 86(1964-8), p. 327.
- (7) Sato, Y., et al., Trans. Japan Soc. Mech. Engrs. (in Japanese), Vol. 48, No. 431(1982-7), p. 1416.
- (8) Lockhart, R. W. and Martinelli, R. C., Chem. Engng. Progr., Vol. 45, No. 1 (1949), p. 39.
- (9) Sadatomi, M., et al., Trans. Japan Soc. Mech. Engng. (in Japanese), Vol. 48, No. 434(1982-10), p. 1893.
- (10) Inoue, A. and Aoki, S., Trans. Japan Soc. Mech. Engng. (in Japanese), Vol. 38, No. 288(1970), p. 1366.
- (11) Katsuhara, T. and Yasuda, Y., Proc. 12th Symp. Heat Transf. (in Japanese), 1975, p. 125.
- (12) Smith, S. L., Instn. Mech. Engng., Vol. 184, No. 36(1969), p. 647.
- (13) Baroczy, C. J., NAA-SR-8171 (1963-4), p. 1.