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Air-water Annular Two-phase Flow in a Horizontal Tube*

(2nd Report, Circumferential Variations of Film Thickness Parameters)

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Experimental investigation was made on circumferential variations of the characteristics of a liquid film formed on the inner surface of a horizontal tube of 26.0 mm I.D. in which air and water flowed concurrently. Superficial velocities of the both phases ranged 10~50 m/s for air and 0.006~0.40 m/s for water. The flow pattern concerned was mainly an annular flow.

Annular flow is subdivided into two regions characterized by liquid slug like frothy liquid lump (A_F -region) and disturbance wave (A_D -region). Classification can be made by examining the shape of the cumulative wave frequency distribution, plotted on normal probability paper against the radial distance from tube inner wall. A new method is proposed for separating base film from disturbance wave, which is processed on the wave frequency distribution chart. Experimental data are presented on principal parameters of liquid film such as thickness of base film, disturbance wave-height, -frequency and -velocity. A consideration is also made on the liquid transportation in disturbance wave region.

Key Words : Multiphase Flow, Annular Two-phase Flow, Horizontal Tube, Circumferential Characteristics, Disturbance Wave, Base Film, Experimental Study

1. Introduction

Gas-liquid two-phase flow in a horizontal tube is frequently encountered in various kinds of steam generators and pipe lines transporting thermal energy with steam-water as a thermal medium. However, fundamental experimental data as well as theory on a two-phase flow in a horizontal pipe line are very few compared with those on one in a vertical pipe line. The present authors have researched a horizontal air-water two-phase annular flow to make clear the mechanism of flow in a pipe line encountered at, for example, a geothermal power station.

In a previous paper⁽¹⁾, the circumferential distributions of time averaged film thicknesses, such as mean, maximum and minimum were investigated and correlated. The results show that the effect of gravity is recognized and the circumferential dis-

tribution of film thicknesses is asymmetric even when gas velocity seems to be sufficiently high. Furthermore, it is suggested that the characteristics of waves^{(2)~(4)} which play an important role in the formation of a liquid film near the top of tube are not circumferentially uniform. Due to the non-uniformity of waves the shear force at gas-liquid interface is also circumferentially non-uniform, the effect of which will reflect on the film distribution. Consequently, to introduce a theoretical model it is important to grasp the information on the circumferentially different characteristics of film thickness.

In this paper, attention was focused on the film thickness of the base film as well as characteristics, such as height, velocity and passing frequency of disturbance waves which may play a more important role in the formation of a liquid film in a horizontal pipe than in a vertical one. Furthermore liquid transport mechanism and the relation between the circumferential distribution of film thickness and the flow pattern are discussed.

2. Nomenclature

- a : Time ratio of residence of disturbance wave
- C : Wave velocity m/s
- D : Inner diameter of tube m
- g : Acceleration of gravity m/s²
- h : Wave height m
- j_g : Volumetric flux density of air m³/m²s
- j_l : Volumetric flux density of water

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- $\text{m}^3/\text{m}^2\text{s}$
 L_D : Distance between two adjacent disturbance waves m
 N_D : Passing frequency of disturbance wave 1/s
 N : Wave number 1/s
 ΔP : Pressure difference across the wave defined by Eq.(1) Pa
 Q_D : Volumetric flow rate of water transported by disturbance waves m^3/s
 Q_T : Total volumetric flow rate of water m^3/s
 S_A : Area under broken line in Fig.22 m^2
 S_B : Area expressed by hatching in Fig.22 m^2
 t_B : Mean thickness of base film mm
 t_f : Film thickness mm
 u_g : Average velocity of gas core m/s
 y : Radial distance from tube wall mm
 γ_g : Specific weight of air N/m^3
 η : Residence time ratio of liquid phase
 θ : Sector angle measured from the top of tube in a cross section degree
 θ_0 : The highest circumferential-position from which liquid film starts to form degree
 λ : Wave length m
 τ : Time required for wave to pass through two axially different stations s

Flow pattern symbols

- A : Annular flow
 F : Froth flow
 Sp : Separated flow

Subscripts

- D : Disturbance wave
 m : Time averaged value
 max : Maximum value
 min : Minimum value
 — : Ensemble averaged value
 $()$: Value at circumferentially local point
 NDP : Value determined from normal probability curve
 NMAX : Value determined at a point where wave number is maximum

3. Experimental Apparatus and Procedure

The test section is made of transparent acrylic resin to observe flow pattern. The inner diameter of the test tube is 26.0 mm and the length from an air-water mixer to an air-water separator is about 6.45 m.

Residence time ratio of liquid phase was detected by a needle contact probe which could be traversed both radially and circumferentially. Time varying hold-up and passing frequency of wave were measured by constant current method (Fukano's method). Static pressure and pressure gradient at the film thickness measuring station were obtained by interpolating data obtained at three axially different locations. Mercury or colored carbon tetrachloride was used as U-type manometer liquid depending on the magnitude of the pressure difference. The details of the flow system, the experimental equipment and procedure were described in the previous paper⁽¹⁾.

Working fluids were air and water. Static pressure was about atmospheric pressure, 0.103~0.128 MPa at the measuring section, and water temperature 9.1~17.3 °C.

4. Results and Discussion

4.1 Range of experiment and flow pattern

Fig.1 shows the range of the flow rates of air and water tested. Data points are designated by marks "o" and "•". j_l and j_g are the volumetric flux densities of water and air, respectively. The thick solid lines show the boundaries of flow patterns observed in the test. "A_D" and "A_F" express the annular flow regime, "F" the froth flow and "Sp" the separated flow⁽¹⁾. In the region under a one-dot-chain line, the height, length and frequency of waves do not change largely with time. In the region above a two-dots-chain line, entrainment is detected by an isokinetic probe of 1.6 mm I.D. fixed at the center of the tube.

- , ● : Data points
 Lines of demarcation
 — Flow pattern
 - - - Existence of two-dimensional wave
 Onset of entrainment
 - - - - A_F and A_D regions
 — S_B/S_A=0.5 (see § 4.6)

Fig.1 Experimental range and flow patterns.

4.2 Residence time ratio of liquid phase

Figs.2(a)~(e) show the typical examples of the distribution of residence time ratios of liquid phase in cases of froth, separated and annular flow. These data are obtained by the needle contact method and plotted on normal probability papers. Abscissa y is radial distance from tube wall and parameter θ is sector angle measured from the top of the tube in a cross section. The shape of curve for $(\eta)_\theta$ is unique depending on flow pattern.

Fig.2(a) is for froth flow. The point of $y=13$ mm on the horizontal axis corresponds to the center of the tube-cross-section. The curves of $(\eta)_\theta$ meet at almost

the same point, $y=13$ mm, irrespective of θ . This is an evidence of the existence of liquid slug, i.e., the flow pattern is froth flow. And it also proves the reproducibility of our data. The common feature of $(\eta)_\theta$ -curve for froth flow is that $(\eta)_\theta$ -curves take different values depending on θ near the bottom of the tube.

Fig.2(c) is for annular flow. It is noticed that each curve has two characteristic regions; a steep-slope-region where $(\eta)_\theta$ decreases rapidly with y and a gentle-slope-region where film thickness increases rapidly. This characteristic of $(\eta)_\theta$ -curve is similar to that of the typical disturbance wave flow in a horizontal duct⁽⁵⁾. Therefore, an annular flow which has a shape of $(\eta)_\theta$ -curve similar to those of Fig.2(c) is referred to as A_F . The gentle-slope-region becomes more conspicuous in the lower portion of the tube. This implies that due to gravity the liquid tends to move toward the bottom of the tube even when it is accompanied by high air flow. Consequently, the film near the bottom is thicker, and disturbance waves are easier to occur in horizontal flow than in vertical flow where distribution of film thicknesses is uniform circumferentially.

As shown in Fig.2(b), in some cases of annular flows, $(\eta)_\theta$ -

curves for $\theta=150^\circ$ and 180° have similar shape to that for froth flow, Fig.2(a), although they show a distribution similar to that of disturbance flow in the upper half of the tube, $0^\circ < \theta < 90^\circ$. Those annular flows are referred to as A_F in this paper. The broken line in Fig.1 shows the boundary between A_D and A_F regions.

Fig.2(d) is a typical example for separated flow. All the flows where the liquid film breaks near the top of the tube are classified as a separated flow in this paper. Under the same flow condition as that of Fig.2(d) a ripple flow is realized if it is in a vertical tube⁽⁶⁾.

Fig.2(e) is another example of separated flow. The shape of $(\eta)_\theta$ -curve, however, is more like that of A_F region. As described before, all the flows without liquid film near the top of the tube belong to the separated flow regime. The difference in the shape between ones shown in Figs. 2(d) and (e), however, may suggest that there is some difference in flow mechanism between the two. Some examination of this problem will be made in §4.6.

4.3 Definition of base film

As seen from the distributions of $(\eta)_\theta$ in Fig.2, there are many cases where disturbance waves with large wave height exist on the base waves with small and uniform amplitude^(6,7). Dual structure, disturbance wave and base film, model may be useful to analyze theoretically the flow mechanism of horizontal annular flow.

One of the authors already proposed a method to divide liquid film into base film and disturbance wave⁽⁷⁾. The method is based on a cumulative frequency distribution curve for film thickness plotted on a normal probability paper and also on the fact that the curve can be approximated by two straight line segments which correspond respectively to base wave and disturbance wave. However, the lines cannot be drawn without difficulty because the general trend of data is curved in some flow conditions. The tendency is more apparent as the tube diameter increases. Therefore, in this paper, another method which uses wave number measured by the

Fig.2 Typical examples for the distribution of residence time ratios of liquid phase.

needle contact method was proposed.

Fig.3 shows a typical example of wave number distribution. Here, N is the local wave number and $N_{\max}$ is the maximum wave number of all the data obtained under the same flow condition. Generally, N increases rapidly with y until the point of $N_{\max}$. Thereafter it decreases gradually as y . This feature is remarkable at the bottom of the tube where disturbance waves are outstanding.

Because the number of tiny bubbles in the liquid film can be neglected compared with wave number at gas-liquid interface, wave number may reach the maximum value when the tip electrode touches the base wave. So, mean thickness of base film is defined by a point at which N takes the maximum. Fig.4 shows the relation between $(t_{Bm})_{NMAX}$ determined by a maximum-wave-number point and $(t_{Bm})_{NDP}$ determined from the intersection of the two straight lines drawn on the normal probability paper. It is revealed that the differences between $(t_{Bm})_{NMAX}$ and $(t_{Bm})_{NDP}$ are within $\pm 30\%$

Fig.3 Example of passing frequency.

Fig.4 Examination for the definition of base film thickness, t_{Bm} .

except at some points of froth flow, separated flow and A_F region. From this result besides that this method has a less arbitrariness than the others, we conclude that the method proposed in this paper is useful to determine the thickness of base film.

Fig.5 shows a typical example of the cumulative frequency function for the time ratio of the existence of liquid phase in the annular flow. Various film thicknesses are determined from the values corresponding to the respective points on the vertical scale as follows; the maximum film thickness, t_{fmax} , and the minimum film thickness, t_{fmin} , are determined respectively from the 0.01% and 99% points on the vertical scale, "a" being the probability of the disturbance wave. And the values of $2(t_{Bm} - t_{fmin}) + t_{fmin}$ and $(t_{fmax} - t_{Bm})$ are defined respectively as the maximum film thickness of the base film, t_{Bmax} , and the disturbance wave height, h_D . Furthermore, the value of $(t_{Bmax} - t_{fmin})$ is defined as the base wave height, h_B .

4.4 Circumferential distribution of thicknesses of base film

Fig.6 shows an example of the circumferential distribution of base-film thicknesses, $(t_{Bm})_\theta$. It is revealed that (1) t_{Bm} increases toward the bottom of the tube, and becomes small with an increasing j_g ; (2) in froth flow t_{Bm} corresponds to the film thickness around gas slug, and there is no fundamental difference between the distribution of $(t_{Bm})_\theta$ of froth flow and that of A_F region (see §4.2); (3) the difference between $(t_{Bm})_0$ and $(t_{Bm})_{180}$ is large in A_F region and froth flow, while it is small in A_D region; and (4) the effect of j_l on t_{Bm} is small at $\theta = 0^\circ$ in the same way as a vertical annular flow, but is large at $\theta = 180^\circ$.

Fig.7 shows the values of t_{Bm} at $\theta = 90^\circ$ and 180° . As seen in the result of $\theta = 90^\circ$, t_{Bm} takes the maximum value at some values of j_g depending on j_l . This is due to two conflicting actions of air flow to main-

Fig.5 Definition of wave characteristics.

tain liquid film; one is lifting action of j_g which can be clearly seen in Fig.8, and the other one is reducing film thickness with j_g . It should be added that broken lines in Fig.8 express water levels for the case of ideal stratified flow. As shown in Figs.9 and 10, the wave height of base film, h_B , is approximately equal to t_{Bm} , and it behaves qualitatively in similar way to t_{Bm} for the variation of j_l and j_g .

4.5 Characteristics of disturbance wave

4.5.1 Circumferential distribution of wave heights

Fig.11 shows a circumferential distribution of the heights of disturbance wave. It is revealed that (1) the wave height, h_p , increases with θ , but the smaller the j_g the higher the increasing rate; (2) h_p decreases with an increasing j_g at the bottom of the tube, while it increases with j_g at the top of the tube except when $j_l=0.40$ m/s and 0.20 m/s; (3) the difference in the wave height between the top and the bottom of the tube becomes small as j_g increases; and (4) h_p increases with j_l . The above

Fig.6 Circumferential distribution of base film thicknesses.

Fig.7 Base film thickness, t_{Bm} .

results are similar to t_{Bm} . However, it is noticeable that the wave height of disturbance wave is large compared with the base film thickness. As shown in Fig.12 almost all the experimental data of h_p/t_{Bm} take values above unity; in particular the value is above 10 when both j_l and j_g are large. Fig.13 shows the wave height of disturbance wave at $\theta=60^\circ$ and 180° . As already shown in Fig.7, t_{Bm} at the bottom of the tube decreases as j_g increases. However, h_p takes almost an equal value under the condition of $10 \text{ m/s} < j_g < 20 \text{ m/s}$. Under the same flow condition h_p/t_{Bm} takes the maximum value near the point of $\theta=120^\circ \sim 150^\circ$ (figure is omitted). This is due to the fact that t_{Bm} increases toward the bottom of the tube (Fig.6), while h_p remains almost constant in the range of $\theta=120^\circ \sim 180^\circ$.

4.5.2 The wave velocity

The velocity of disturbance wave was determined from the delay time of a maximum peak in the cross-correlation function of the signals of time varying liquid film thicknesses which were detected by the constant current method at two different locations with a separation of 217 mm. The data used for the analysis were 50 ~ 120 disturbance waves. The solid lines in

(Broken lines show the water level for the case of the ideal stratified flow.)

Fig.8 The highest circumferential position, θ_0 , where liquid film forms.

Fig.9 Circumferential distribution of base wave heights.

Fig.14 show the wave velocity of disturbance wave. They are compared with that in the vertical up-flow which is shown by broken line. It is revealed that (1) C_D increases as j_l and/or j_g increases; and (2) generally, C_D is larger in vertical up-flow than in horizontal flow. However, in some conditions, for example at $j_l=0.20$ m/s, C_D for horizontal flow is larger than that for vertical up-flow. The difference in C_D due to the difference in the orientation of the test section becomes small when j_g is large. Even in froth flow, C_D is considerably smaller than the velocity of water slug, the sum of j_g and j_l .

One of the authors proposed a pressure difference, ΔP , across a disturbance wave as an important factor to determine its velocity⁽⁷⁾. ΔP is calculated by assumptions; (1) air flow is separated in front of the wave, (2) the pressures at the front of and behind the wave are equal to that at the crest of the wave and the average of the pressure behind the wave, respectively. Then ΔP is obtained from Bernoulli's equation as;

$$\Delta P = \gamma_g \cdot \{ (u_{g1} - C_D)^2 - (u_{g2} - C_D)^2 \} / 4g \dots (1)$$

Here, u_{g1} and u_{g2} are the cross-sectional average velocities of gas; they are calculated respectively from the areas in the cross-section of base film and at the crest of the disturbance wave estimated from the contour of the maximum wave height.

Fig.15 shows the relation between C_D and ΔP calculated by Eq.(1). It is revealed that C_D increases with an increasing j_g for a given ΔP , and C_D is generally correlated well by ΔP . However, data points marked with short cross bars indicate somewhat gradual changes with ΔP compared with that in the other region. This is possibly due to the effect of surface tension. Because the data are in the region under the one-dot-chain line in Fig.1.

4.5.3 Passing frequency, wave length and scale of disturbance wave

Figs.16~18 show the passing frequency, N_D , the wave length, λ_D , and the dis-

Fig.10 Base wave height, h_b .

(Experimental points with a short cross bar are under the one-dot-chain line in Fig.1.)

Fig.11 Circumferential distribution of disturbance wave heights.

Fig.12 $h_D / \tau_{Bm} - \theta$.

(Data points with oblique lines and short cross bars show those in froth flow and in the region under the one-dot-chain line in Fig.1 respectively.)

Fig.13 Disturbance wave height, h_D .

tance, L_D , between two adjacent disturbance waves against j_g , respectively. N_D was determined from the frequency corresponding to the largest peak of power spectrum density function of output detected by the constant current method. λ_D is calculated from C_D/N_D and L_D is from $\lambda_D(a/100)$ respectively⁽⁷⁾. Broken lines are used for the vertical up-flow in Figs.16 and 17. It is revealed that N_D increases with j_g and asymptotically approaches a constant value which decreases slightly with j_1 when $j_g >$

(For the meaning of marks, refer to the caption of Fig.13.)

Fig.14 Disturbance wave velocity, C_D .

(For the meaning of marks, refer to the caption of Fig.13.)

Fig.15 $C_D - \Delta P$.

(For the meaning of marks, refer to the caption of Fig.13.)

Fig.16 Passing frequency of disturbance wave.

40 m/s. In this condition, λ_D depends largely on j_1 in the case of horizontal tube. On the other hand λ_D takes an identical value regardless of j_1 in the case of vertical up-flow. Generally, L_D takes a value smaller than 0.2 m at almost all the experimental points.

Fig.19 shows the relation between the wave height $h_D (= (t_{fmax})_\theta - (t_{Bm})_\theta)$ and the distance, L_D . There is a positive correlation between h_D and L_D , which means that a wave with a large wave height has a large

(For the meaning of marks, refer to the caption of Fig.13.)

Fig.17 Wave length, λ_D .

(For the meaning of marks, refer to the caption of Fig.13.)

Fig.18 Distance between two adjacent disturbance waves.

(For the meaning of marks, refer to the caption of Fig.13.)

Fig.19 $\bar{h}_D - L_D$.

scale in the direction of tube axis.

4.5.4 Fluid transportation in disturbance wave flow

The liquid amount transported by a disturbance wave, Q_D , is calculated from the equation below,

$$Q_D = \pi \left\{ (D/2 - \bar{t}_{Bm})^2 - (D/2 - \bar{t}_{fm})^2 \right\} \cdot C_D \dots (2)$$

Fig.20 shows the result calculated by Eq.(2) and the data on vertical up-flow which are indicated by broken line. Compared keeping j_1 constant, Q_D is larger in the vertical up-flow than in the horizontal flow when $j_g < 40$ m/s. On the contrary, when $j_g > 40$ m/s it is large in the horizontal flow. This is explained as follows; (1) when $j_g < 40$ m/s, the mean film thickness is larger in vertical up-flow, and in the horizontal flow the wave height of distur-

(For the meaning of marks, refer to the caption of Fig.13.)

Fig.20 $Q_D - j_g$.

(For the meaning of marks, refer to the caption of Fig.13.)

Fig.21 $Q_D/Q_T - j_g$.

bance wave at the top is much smaller than that at the bottom. Meanwhile, in the vertical up-flow, disturbance waves have nearly the same height as one at the bottom of the horizontal pipe⁽⁶⁾, and (2) when $j_g > 40$ m/s, the difference in hold-up between the horizontal and the vertical flows is small. The film thickness at the bottom of the tube in horizontal flow, however, is larger than that in vertical up-flow, consequently disturbance wave in horizontal flow can be formed with greater ease. The ratio of Q_D to total volumetric flow rate of water, Q_T , is shown in Fig.21. Even in the case of small j_1 and large j_g , Q_D/Q_T takes a large value. As described in §4.2, this is due to the fact that disturbance wave occurs almost always in horizontal flow at the bottom of the tube.

4.6 Relation between the circumferential distribution of film thicknesses and the flow pattern

The solid line in the picture in the bottom right-hand corner of Fig.22 shows the circumferential distribution of mean film thicknesses, $(t_{fm})_\theta$, and the broken line shows the water surface obtained by supposing that water flows as an ideal stratified flow with the same liquid hold-up as in the actual flow. Put the sum of areas indicated by hatching as S_B and the area under the broken line as S_A . Calculated S_B/S_A are plotted in Fig.22. It is revealed that the volume of liquid lifted up on the tube surface increases with j_g . As a measure of the effect of gas velocity on the lifted liquid amount $S_B/S_A = 0.5$ is adopted. By this measure the data points are successfully divided into two regimes

Fig.22 $S_B/S_A - j_g$.

as shown in Fig.1 where thin solid line is the boundary. The right side of the line corresponds to the region of $S_B/S_A \geq 0.5$, and left side the region of $S_B/S_A < 0.5$. This line happens to agree with the demarcation line between A_F and A_D regions in the annular flow regime. And in the separated flow regime it agrees with a demarcation line in the left side of which approximately identical waves only can be observed. Liquid flow rate is much higher at the bottom of the tube even though $S_B/S_A = 0.5$. With these facts in mind, it may be better from the viewpoint of flow mechanism to divide the separated flow and the annular flow by the fine solid line than the thick solid line which is determined by superficial appearance, i.e., whether liquid film exists on all the tube surfaces or not.

The effects of physical properties of fluids and pipe diameter on the parameters discussed in this paper will be examined in future experiments.

5. Conclusions

Experiments were conducted on a horizontal air-water annular two-phase flow. Attention was paid to the characteristics of time varying component of liquid film. The circumferential variations of film thickness parameters were examined. The main results are summarized as follows:

(1) Annular flow is subdivided into two regions; the disturbance wave region (A_D -region) and A_F -region which is adjacent to the froth flow region. The cumulative time ratio of existence of liquid phase, $(\eta)_\theta$ -curve, in A_F -region has a similar shape to that of froth flow.

(2) Judging from the shape of $(\eta)_\theta$ -curve, disturbance wave occurs in almost all the test runs in horizontal flow even under the same flow condition under which ripple flow is observed in the vertical up-flow, because water generally deflects to the bottom due to gravity in horizontal tube.

(3) The higher the gas flow rate, the higher the liquid film climbs toward the top of the tube. The amount of liquid climbing on the tube surface is closely related to the flow configuration classified

by the shape of $(\eta)_\theta$ -curve, which suggests the possibility of quantitative classification of flow patterns.

(4) A new method is proposed in this paper for separating disturbance wave from base film. It is based on a wave frequency distribution curve and has a less arbitrariness to determine a point at which two lines which represent respectively the disturbance wave and base wave meet. The difference in the base film thicknesses determined by this and the former methods is small.

(5) The liquid amount transported by disturbance waves is generally large. In particular it is larger in horizontal tube than in vertical one in case of large j_g . This is because the disturbance wave is apt to occur at the bottom in the horizontal tube.

(6) Detailed informations on the base film as well as the characteristics of disturbance wave, such as thickness of base film, disturbance wave-height, -frequency, -velocity, -length and -scale which are useful for analyzing theoretically the flow mechanism of liquid film are obtained.

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References

- 1) Sekoguchi,K., et al., Bulletin of the JSME, 25-208(1982), 1559.
- 2) Butterworth,D., Progr. Heat Mass Transfer, 6(1972), 235.
- 3) Fisher,S.A., et al., Proc. 6th Int.Heat Transfer Conf., Toronto, 2(1978), 49.
- 4) Fisher,S.A. and Pearce,D.L., Two-Phase Momentum, Heat and Mass Transfer in Chemical, Process and Energy Engineering Systems, 1(1979), 327.
- 5) Fukano,T., et al., Bulletin of the JSME, 22-172(1979), 1374.
- 6) Sekoguchi,K., et al., Trans. JSME (in Japanese), 39-317(1973), 313.
- 7) Fukano,T., et al., Bulletin of the JSME, 24-191(1981), 781.