Air-Water Two-Phase Annular Flow in Near-Horizontal Tubes*

(Effect of Pipe Inclination on the Fundamental Parameters)

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An experimental investigation was made into hold-up, frictional pressure drop and circumferential distribution of film thickness of an air-water two-phase annular flow in horizontal and near horizontal tubes of 26.0 mm ID. Superficial velocities of both phases ranged from 10 m/s to 50 m/s for air and from 0.002 m/s to 0.40 m/s for water. The measured values of those physical quantities and the highest circumferential location from which liquid film starts to form toward the tube bottom are presented, and the effects of the inclination angle on them are examined. As a result, it was made clear that the effect of the inclination on these parameters, even if it is within a small angle, could not be neglected and that the mean film thickness averaged over the circumference of the tube was approximately equal to the local film thickness at $\theta = 120^\circ$ independent of the inclination.

Key Words: Multiphase Flow, Annular Two-Phase Flow, Horizontal and Near Horizontal Tubes, Film Thickness, Hold-up, Pressure Drop

1. Introduction

The pipelines transporting a steam-water two-phase mixture from steam producing wells to a separator in geothermal power plants are usually inclined because many areas utilizing the terrestrial heat are in the mountains in Japan. The helical coil used for a steam generator, a superheater and a reheater in the power plant of a fast breeder reactor are other examples of inclined pipelines. Furthermore, in a fluidized bed boiler which is advantageous for burning low quality fuel, horizontal and inclined pipelines are used.

Although a gas-liquid two-phase flow in a horizontal or a near horizontal pipeline is encountered in many practical pieces of equipment, few investigations have been done on the flow mechanism of the

annular flow in these pipelines and even fundamental data are lacking at present⁽¹⁾⁻⁽¹⁰⁾. Therefore, in a geothermal power plant, for example, two-phase pipelines are set so that the inclination angle does not exceed a certain value, 12° for example, assuming that a two-phase flow in a pipeline with a small inclination angle is similar to that in a horizontal pipeline.

The authors have already clarified the effect of the pipe inclination on the detailed flow pattern transition in the annular flow regime⁽¹¹⁾. The purpose of this investigation is to obtain fundamental data and to correlate them for planning a horizontal or a near-horizontal pipeline which contains a gas-liquid annular flow.

2. Nomenclature

D : Inner diameter of tube mm
 j_g, j_l : Volumetric flux of air and water, respectively
 $\text{m}^3/\text{m}^2\text{s}$
 $\bar{h}_D$: Time and circumferentially averaged wave
 height mm
 ΔP_{TP} : Frictional pressure drop for two-phase flow
 Pa
 $\Delta P_{g0}, \Delta P_{l0}$: Frictional pressure drop due to gas and

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- liquid flowing alone at a rate of j_g and j_l , respectively Pa
- R : Inner radius of tube mm
- r : Radial distance ($\equiv R - y$) mm
- t_{fm} : Average circumferential liquid film thickness mm
- $(t_{fm})_\theta$: Time-averaged local film thickness mm
- X : Martinelli parameter ($\equiv \sqrt{\Delta P_{t0}/\Delta P_{g0}}$)
- y : Radial distance inward from the inner tube surface mm
- $y_{0.35}$: Distance y at which $(\eta)_\theta = 0.35$ mm
- α : Inclination angle measured from the horizontal degree
- η : Time ratio of existing liquid phase
- η_t : Hold-up
- θ : Circumferential position expressed by an azimuthal angle from the top of the tube degree
- θ_0 : Circumferential position from which the liquid film forms downward degree
- ϕ_t : Two-phase friction multiplier ($\equiv \sqrt{\Delta P_{TP}/\Delta P_{t0}}$)
- Suffix**
- C : Value obtained by the constant current method
- N : Value obtained by the needle contact method
- tt : Turbulent liquid and turbulent gas flow
- vt : Viscous liquid and turbulent gas flow
- Flow pattern symbol**
- A : Annular flow (A_D : annular flow with typical disturbance wave, A_F : annular flow with slug-like liquid lump)
- F : Froth flow
- S_P : Separated flow

3. Experimental Apparatus and Procedure

Figure 1 shows a schematic diagram of the exper-

Fig. 1 Schematic of the experimental apparatus

imental apparatus. Air supplied from a compressor and water from a constant head tank are introduced into an air-water joining section after their flow rates are measured individually by orifice flow meters. The air-water mixture flows through the tube into an air-water separator, where air is released into the atmosphere and water is measured more accurately by weighing if necessary.

A smooth tube with an inner diameter of 26.0 mm and total length of 6.7 m is made of transparent acrylic resin to observe the flow pattern. Figure 2 shows the details of the air-water joining section. Water is introduced into the tube as a water film through a porous tube with a porosity of 120 μm , in the core of which air is flowing at high velocities.

Static pressures are detected at different three axial locations, $P_1 \sim P_3$, as shown in Fig. 1. Mercury or colored carbon tetrachloride ($\gamma = 1.562 \times 10^4 \text{ N/m}^3$, 20°C) was used as a U-type manometer liquid depending on the magnitude of the pressure difference.

Film thickness was measured at about 3.7 m (142 D) downstream of the air-water joining section by two different types of device; one is the needle contact method⁽¹²⁾ and the other is the constant current method which was originally developed by Fukano⁽¹³⁾ as shown in Figs. 3(a) and (b), respectively.

The device for the needle contact method consists of a pair of electrodes. One is a tip electrode which can be traversed both radially and circumferentially, and the other is a fixed electrode mounted flush with the inner surface. Therefore the local value of the time ratio of the existing liquid phase can be measured. The circumferential measurements are made at seven locations; i.e., every 30° from the top to the bottom of the tube. A slice level for analyzing residence time ratio is taken as 0.35 from the water level.

As for the constant current method, a pair of sensor electrodes with 1 mm in thickness are set 5 mm apart from each other, and flush with the inner surface. Three pairs of sensor electrodes are set in three different locations (Tap 1 through Tap 3) at a 217 mm

Fig. 2 Details of air-water joining section

(a) Needle contact method

(b) Constant current method

Fig. 3 Measuring devices for hold-up

intervals along the tube axis as shown in Fig. 3(b). Output signals from these taps are sent respectively through amplifiers with very high input impedance into a data recorder and a direct visual oscillograph. The data presented in this report are detected at Tap 1 located 856 mm downstream of the needle contact probe.

By the constant current method, the instantaneous hold-up can be measured, while by the needle contact method only the time-averaged hold-up can be obtained by integrating the whole circumstances of the tube. The output signal from the constant current method becomes larger as the film thickness becomes small, signifying that the constant current method is more useful than the needle contact method when hold-up is very small.

The experimental conditions are as follows. Inclination angles of the test tube: -10° , 0° , 10° and 15° to the horizontal. Working fluids: air and water. Static pressure: $(0.102 \sim 0.135)$ MPa. Water temperature: about 20°C . Ranges of superficial velocity and superficial Reynolds number of air: $j_i = (10 \sim 50)$ m/s, $Re_g = (1.77 \sim 10.1) \times 10^5$, and those of water: $j_i = (0.002 \sim 0.40)$ m/s, $Re_l = 18 \sim 1.04 \times 10^4$. Flow pattern observed is mainly annular flow.

4. Results and Discussion

Circumferential liquid film distribution

Figure 4 shows a typical example of the liquid hold-up $(\eta)_\theta$ plotted against the distance from the tube wall. The parameter θ is the angle as shown in the figure. The local mean film thickness $(t_{fm})_\theta$ is defined by the following equation

Fig. 4 Typical results about the time ratio of existing liquid phase, $(\eta)_\theta$, against distance from tube wall, y . (Mark "x" designates the point where y equals $(t_{fm})_\theta$.)

$$(t_{fm})_\theta = R - \sqrt{R^2 - 2 \int_0^R (\eta)_\theta r dr} \quad (1)$$

where η means the existing time ratio of liquid phase.

The mark "x" in Fig. 4 indicates $(t_{fm})_\theta$ in each curve. Figures 5(a) and (b) show the relationships between $(t_{fm})_\theta$ and the distance y where $\eta = 0.35$, and $y_{0.35}$. It is revealed that $(t_{fm})_\theta$ can be estimated from $y_{0.35}$ within $\pm 20\%$ error. This relation was discovered experimentally in the ripple region of a vertical upward annular flow⁽¹²⁾, where the wave heights were

Fig. 5 Relation between $(t_{fm})_\theta$ and $y_{0.35}$

Fig. 6 Flow configuration and its circumferential distribution of film thickness

lower than those in this experiment which includes the froth, separate and annular flows.

Figures 6(a)~(f) show the circumferential distributions of local mean film thickness and flow configurations. In the case of $j_g \approx 10$ m/s [Fig. 6(a)], the whole tube wall was covered with a liquid film only when α was positive, i. e., the upward flow, where the flow pattern was froth flow with definite liquid slugs. So the liquid film was formed at the top of the tube even when the gas flow rate was low. On the other hand, in the case of $\alpha=0^\circ$ or -10° the film thickness is smaller than that of the upward flow even at the bottom of the tube.

When j_g is higher than 15 m/s, [Figs. 6(b) and (c)], a liquid film usually climbs the tube wall. Generally, as α increases, the film thickness and also the wave height become large at the bottom. By the action of these waves, especially disturbance wave, the film can be formed at a higher position of the tube wall. This tendency is clearly seen in Fig. 7. The ordinate θ_0 in this figure is the position from which a liquid film forms. In the case of $j_g=20$ m/s and $j_l=0.04$ m/s, θ_0 certainly decreases with increasing α .

Close inspection of Fig. 7, however, reveals that the dependence of θ_0 on α is divided into the following three types depending on the magnitude of j_g ; (a) the dry area decreases with α ($10 \text{ m/s} \leq j_g < 15 \text{ m/s}$), (b) the dried area is the largest in the case of horizontal flow ($20 \text{ m/s} < j_g < 30 \text{ m/s}$), and (c) the dry area increases with α if j_l is small ($40 \text{ m/s} < j_g$).

The relation between θ_0 and α is significantly affected by the flow configuration. In the first case (a) the flow pattern was froth flow in the upward flow ($\alpha < 0^\circ$) and separated flow in the horizontal and

downward flows ($\alpha=0^\circ$ and $\alpha < 0^\circ$). When j_g is low, as in this case, the gravitational force has a much larger effect on the liquid flow than the interfacial shear force has. So the film thickness as well as the scales of liquid lump and waves become larger at the bottom with α . These waves have the effect of making a liquid film spread toward the top. As a result the dry area becomes narrower.

In the second case (b), the liquid flow at the bottom becomes like a froth flow if α becomes large in the upward flow ($\alpha > 0^\circ$), and the liquid lumps wet the upper part of the tube. As α decreases the number of liquid lumps rapidly decrease and the axial distribution of the hold-up becomes more uniform. If α is reduced further, $\alpha < 0^\circ$, the flow becomes more like a disturbance wave flow, while the thickness of the base film is smaller than that when $\alpha=0^\circ$. Due to the disturbance waves, the liquid film climbs the tube wall. Therefore, the dry area at the top of the tube is largest in the case of horizontal flow. The flow rate of liquid transported by disturbance waves is quite large in the A_D regime^{(14),(15)}. According to the visual observation, the disturbance waves appeared in the A_D regime play a more important role in creating a liquid film in the upper part of the tube than the rather uniform waves on the interface do in the case of $\alpha=10^\circ$.

In the third case (c), all flow patterns always belong to the A_D regime independent of the orientation of the pipe. In such a flow, the larger the wave height, the more the disturbance wave promotes formation of a liquid film. As shown in Fig. 8, the larger the inclination angle α , the smaller the $\bar{h}_D$ becomes, especially when j_l is so small that the liquid film is easy to break down at the tube top. As a result, the action of disturbance wave in forming a liquid film is weakened, and θ_0 increases with α .

At high j_g [Figs. 6(d), (e) and (f)] the film

Fig. 7 Circumferential starting point of liquid film formation

Fig. 8 Effect of pipe inclination on wave height

thickness distribution becomes progressively uniform as j_g increases. However, the effect of α , or the gravitational force, on the film thickness distribution cannot always be neglected, as shown by the fact that the film thickness for $\alpha = -10^\circ$ is smaller than that for $\alpha = 15^\circ$.

Hold-up due to liquid film

Figures 9(a)~(d) show the hold-ups η_{lc} obtained by the constant current method⁽¹³⁾ and η_{IN} calculated from the film thickness distribution curves obtained by the needle contact method⁽¹²⁾ shown in Fig. 6 for example. The abscissa X is the Martinelli parameter. η_{IN} agrees well quantitatively with η_{lc} . So it may be concluded that both devices are useful to measure the liquid film hold-up. The correlations proposed by Lockhart & Martinelli⁽¹⁶⁾ and by Chisholm⁽¹⁷⁾ are plotted in the figures. Generally, the

measured η_i is smaller than the Lockhart & Martinelli prediction, especially in the high j_g region. The difference probably due to the fact that the measured hold-up does not include the hold-up of entrained droplets, the amount of which increases as the gas flow increases.

In the case of horizontal flow, almost all the data are included in the region between the L-M curve and the Chisholm correlation. For the upward flow, however, experimental data tend to be located above the L-M curve. The present two devices cannot measure the hold-up due to the entrained droplets, liquid films flowing as rivulets and isolated droplets on the dry surface. The amount of these isolated liquids increases with α . Therefore, the difference in η_i between the L-M prediction and the measured value becomes larger with α . This fact signifies that the L-

Fig. 9 (a)~(d) Correlation of hold-up

M curve, as well as the Chisholm correlation, should be used carefully to predict the hold-up in a vertical pipeline.

Figure 10 shows the dependence of the hold-up due to liquid film on the flow condition, j_g and j_l , and the inclination angle, α . From this figure it is revealed that η_l is affected considerably by the inclination angle of the tube even when it is rather small. That is, η_l usually increases with α when j_g and j_l are small. This contradicts the results obtained by Guzhov et al.⁽⁵⁾.

Simple method for measuring the liquid film hold-up

Assuming that the liquid film distribution is circumferentially uniform, the mean film thickness t_{fm} is calculated from the hold-up data as follows:

$$t_{fm} = R(1 - \sqrt{1 - \eta_l}) \quad (2)$$

The t_{fm} thus obtained agrees with an accuracy of $\pm 20\%$ with the time-averaged value of t_{fm} measured at the location $\theta = 120^\circ$, $(t_{fm})_{120}$, in the case of horizontal flow⁽¹²⁾. This also holds true for the inclined pipeline as shown in Figs. 11(a)~(d). The scattering of data is within $\pm 10\%$ except for separated flow data.

As already shown in Figs. 5(a)~(b), the time-averaged mean film thickness at any θ , $(t_{fm})_\theta$, is approximated by $y_{0.35}$. From these examinations, it is concluded that what we must do in order to obtain a mean film thickness averaged circumferentially, i.e., hold-up, is, at first, to determine experimentally the η curve at $\theta = 120^\circ$ which expresses the time ratio of the existing liquid phase, η , plotted against the distance from the tube wall, y . The 0.35 point on the η axis corresponds to the estimated mean film thickness, t_{fm} , on the y axis.

Frictional pressure drop

Frictional pressure drop strongly depends on the

Fig. 10 Hold-up

flow pattern, and it usually controls the total pressure drop in the case of an annular flow. Many data and correlations of the frictional pressure drop have been presented, for example, by Lockhart and Martinelli⁽¹⁶⁾, and Chisholm & Laird⁽¹⁷⁾ for horizontal pipes, and by Beggs⁽²⁾ and Spedding & Chen⁽⁷⁾ for inclined pipes. However, the Spedding's curve, for example, has a low accuracy and is troublesome to use. The Lockhart & Martinelli curve, the accuracy of which better than Spedding's, has not been tested for its usefulness in such small Martinelli parameter range as found in the present work. Moreover, no detailed investigation on the effect of the pipe inclination on the frictional pressure drop ΔP_{TP} has been carried out.

In Fig. 12, the experimental data of ΔP_{TP} are plotted against j_g . Generally, as j_g increases, ΔP_{TP} increases and the difference in ΔP_{TP} caused by pipe inclination becomes small. Compared with j_g and j_l kept constant, ΔP_{TP} takes the smallest value in the case of $\alpha = -10^\circ$. Both the steam and water flow rates in an actual geothermal power plant correspond to the flow conditions with larger gas and liquid flow rates region in the present experiment. Then the error in the prediction of ΔP_{TP} for an actual inclined pipeline

Fig. 11 Correlation of the mean film thickness t_{fm} with the local film thickness measured at $\theta = 120^\circ$, $(t_{fm})_{120}$

under the limited flow conditions may be inappreciable even when ΔP_{TP} is estimated from the data for the horizontal flow.

Next, the applicability of the L-M curve to the prediction of pressure drop in the inclined pipe flow will be examined. In Fig. 13, the experimental data of the two-phase friction factor are plotted against X for the cases of $\alpha=15^\circ, 10^\circ, 0^\circ$ and -10° . Solid lines represent the L-M curves of ϕ_{ltt} and ϕ_{lvt} . For the

Fig. 12 Frictional pressure drop

Fig. 13 Comparison of measured data with the Lockhart-Martinelli correlation

horizontal flow the ϕ_{ltt} and ϕ_{lvt} curves agree well with the experimental data under the corresponding flow condition⁽¹²⁾. On the other hand, for the inclined pipe flow, ϕ_{ltt} agrees well with the experimental data, while ϕ_{lvt} does not. The difference between ϕ_{lvt} and the measured value becomes larger with increasing α .

Relationship between hold-up and friction factor

Akagawa⁽¹⁾ has investigated the relationship between the friction factor ϕ_l and the hold-up η_l by using four test sections of different inclination angles of $0^\circ, 30^\circ, 60^\circ$ and 90° , and proposed the next correlation,

$$\phi_l^2 = \eta_l^{-z} \quad (3)$$

where z varies between 1.4 and 2.0 depending on the inclination angle. This relation has been verified in the rather larger hold-up region only, ($0.3 < \eta_l$). The L-M correlation has also not been proven useful in such a small η_l as the present experiment.

In Fig. 14, all the experimental data of ϕ_l except for the case of the froth and separated flows are plotted against η_l . Close inspection of this figure

Fig. 14 Relation between the hold-up and the friction factor

reveals that following; the slope of the solid line expressing the relationship between ϕ_i and η_i is independent of the pipe inclination, and this relationship is expressed by the next equation over a wide range of η_i .

$$\phi_i^2 = \eta_i^{-1.90} \quad (4)$$

This is identical with Eq. (3) with $z=1.9$, which corresponds to the case of $\alpha=30^\circ$ in the Akagawa's experiment.

Although the validity of Eq. (4) is examined for a limited flow pattern i. e. annular flow, Eq. (4) is useful to estimate ϕ_i , or η_i , with an accuracy of $\pm 20\%$ independent of the inclination angle if it is small.

Conclusion

The dependence of the fundamental two-phase flow parameters on the pipe inclination angle α is experimentally investigated for an annular flow in a slightly inclined pipeline of $-10^\circ < \alpha < 15^\circ$. The results are summarized as follows.

(1) The circumferential distribution of film thickness depends on α , and is not uniform even at a high gas flow rate.

(2) The circumferential location from which a liquid film forms is affected by α as well as j_g . This is due to the characteristics of interfacial large waves, which play an important role in forming liquid film, changing with α and j_g .

(3) A simple method for measuring the time averaged hold-up is proposed.

(4) The hold-up η_i and the friction factor ϕ_i can be correlated in the annular flow region by the equation, $\phi_i^2 = \eta_i^{-1.9}$ with an accuracy of $\pm 20\%$.

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