An Investigation of the Flow Characteristics in
the Disturbance Wave Region of Annular Flow*
(1st Report, Effect of Tube Diameter)

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A computer-aided data reduction method was newly developed for determining principal flow parameters on disturbance wave and liquid film in gas-liquid two-phase annular flow. Hold-up data on magnetic tape were processed by computer to discriminate disturbance wave from base-film based on the proposed criteria and to evaluate flow parameters with substantial reduction of time and labor.

Four test tubes of 8, 12, 18 and 26 mm bore were employed, and time-varying liquid hold-up was recorded by means of the constant-current method. The flow parameters computed were velocity, frequency, separation distance and height of disturbance waves, base-film thickness, and superficial film thickness. It was found that most of the flow parameters present a maximum or minimum with the tube of 12 mm bore.

Key Words: Multiphase Flow, Thermal Engineering, Annular Flow, Flow Characteristics, Disturbance Wave, Liquid Holdup, Flow Parameters, Data Processor

1. Introduction

In the disturbance wave regime of gas-liquid two-phase flow there appear not only various heights of waves, including disturbance waves characterized with their remarkably higher crests compared with those of ripples, but also entrainment of liquid droplets from the crests and their deposition on the base film. Such an annular-mist flow has been studied on its flow mechanisms for providing a design basis of thermal systems using steam-water mixtures as the working fluids.

Several analytical models on the annular flow have so far been proposed, among which a modeling was made by one of the authors based on a concept that the flow of liquid phase consists of three major parts such as entrained droplet, disturbance wave, and base film. Establishment of this model required laborious work to reduce the experimental data. At that time of the work(1966) four or five electric signals of wave and film thickness were recorded on

oscillograph paper, and reading these signals was a manual work. The consumed amount of oscillograph paper attained about 3000 m in length, and the total length of the recorded signals was far over 10,000 m only for a test tube. Therefore, it is obvious that such a slow and laborious data-processing employed so far prevented progress in this field.

The present study introduced a computer-aided-data-processing free from such trouble, in which the information of waves and film thickness was recorded on magnetic tape by the constant current method, and disturbance waves were automatically extracted. Main flow parameters were also evaluated through computer-aided-processing. In consequence time and labor required for such a kind of study could greatly be reduced. This paper describes the newly developed data-processing and presents a series of experimental data concerning the effects of tube diameter upon various flow parameters in annular flow except for the information of droplets.

2. Notations

D : Diameter of tube, m, mm
 j_g, j_l : Superficial velocities of gas and liquid phases, m/s
 H_{dm} : Mean height of disturbance wave, m, mm
 L : Axial distance, m
 n : Passage frequency of liquid phase, Hz
 n_d : Passage frequency of disturbance wave, Hz
 N_d : Mean passage frequency of disturbance wave, Hz
 t_f : Liquid film thickness, m, mm
 t_{fb} : Base film thickness, m, mm
 t_{fm} : Mean film thickness, m, mm

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- u_d : Velocity of disturbance wave,
 m, mm
 y : Radial distance from tube wall,
 m, mm
 α : Void fraction
 η : Liquid hold-up
 η_d : Hold-up of disturbance

3. Experimental

Figure 1 shows a schematic diagram of the apparatus used in this experiment. Test sections were transparent acrylic resin tubes with four different diameters of 8, 12, 18 and 26mm. Air and distilled water were fed to an air-water mixer M at the bottom of the test section. The air-water mixture flowed vertically upwards through the test section and was finally separated into the individual phases by a cyclone separator CS. The separated water returned to a circulation pump CP. Porous bronze tube was used as the air-water mixer. Air was axially fed from the bottom of the test section, while water was radially supplied through the porous tube. The ranges of air and water flow rates covered were those for the disturbance wave regime in annular flow.

The constant current method was employed for the measurement of liquid holdup as shown in Fig.2. Electric current supplied from a constant current generator was led between a pair of electrodes 1, and was kept at a specific value during a test run. Two sets of liquid hold-up detector taps were mounted flush with the inner wall between the electrodes 1. Voltage signals from the detector taps were recorded by a data recorder 5 through an amplifier 3.

Relationship between a detected value of voltage, V_{TP} , and its corresponding liquid hold-up, η , is derived by considering the electric resistance of the liquid contained within a pair of holdup detector taps. Neglecting the electric conductance of air compared with that of water, the hold-up is expressed by

$$\eta = V_i / V_{TP} \quad (1)$$

Then the void fraction is written as

$$\alpha = 1 - V_i / V_{TP} \quad (2)$$

Fig.1 Schematic diagram of experimental apparatus

where V_i is the voltage the flow of water alone for ($\eta = 1$) and V_{TP} the voltage for the two-phase flow at the same electric current.

The detected value of voltage is a function of the magnitude of the charged current, i_c , the tube diameter, the spacing between the detector taps, the gain of the amplifier, the electric resistivity of the liquid and the void fraction; thus, denoting the voltage by V_c , an expression for V_c is

$$V_c = C i_c / (1 - \alpha) \quad (3)$$

where C is a proportional constant depending upon the measuring system employed. The determination of the value of C was carried out for every test run. Then several acrylic rods with different diameters were prepared, and each of them was inserted into the test section to produce known magnitudes of α . According to the calibration results, C is independent of α -value.

Void fraction to be measured is obtained from the charged current i , the detected voltage V_{TP} , and the calibrated value of C using the following equation.

$$\alpha = 1 - C i / V_{TP} \quad (4)$$

The dimensions of test tubes and electrical measuring sections (L1 through L5 as shown in Figs.1 and 2) are given in Table1. The spacing of conductance detectors L3 was set at less than the mean separation distance between waves; i.e. about 100 mm for an 8 mm tube, or about 200 mm for a 25 mm

D mm	L1 mm	L2 mm	L3 mm	L4 mm	L5 mm
8	5200	3100	50	1000	4
12	5200	3100	65	1000	4
18	5200	3100	74	1000	4
26	5650	4200	100	600	7

Table 1 Dimensions of test section

Fig.2 Schematic of the constant-current method for liquid hold-up and disturbance wave velocity measurements

tube. The spacing of the detector taps 15 was chosen as 4 and 7 mm, that is sufficiently less than averaged lengths of disturbance wave to be detected.

Flow conditions tested are as follows; pressure: 1.05-1.3 10 N/m, temperature: 30-39°C, superficial air velocity: 20-50 m/s (20 and 30 m/s for a 26 mm tube), and superficial water velocity: 0.04-0.14 m/s.

4. Data Reduction

A data processing method for determining main parameters of annular flow was developed, which largely saves labor and time. Experimental data may be processed real-time if a microprocessor is available.

4.1 Velocity of disturbance wave

Two different procedures were used for measuring the velocity of disturbance wave, u_d . Output signals from both the conductance detectors were first recorded on magnetic tape, and then on oscillograph paper. An example of these signals is shown in Figure 3, where the ordinate corresponds to wave height. Disturbance waves can be easily specified with their distinguished height. Transit time, τ_d , from the upstream to the downstream conductance detector is measured as a time difference between corresponding crests of disturbance waves. The maximum deviation of the transit times measured in this experiment was $\pm 15\%$ from the averages, which were evaluated by about thirty experimental values a test run.

The other determination of τ_d was made using a cross-correlation between the upstream and downstream signals including about one hundred to seven hundred disturbance waves takes a maximum value when the cross-correlation lag is equal to the transit time. Thus determined values coincided with those by the former procedure within a deviation of 5%.

4.2 Computer-aided-processing of data

Prior to the computer-aided-processing of data, analogue signals of void fraction were converted into digital values with the following considerations.

- (1) Sampling frequency is set so high that a disturbance wave is represented by ten or more digital values. Referring to Fig.4, it is determined as 3 KHz.
- (2) Sampling time is long enough to allow the passage of one hundred or more disturbance waves, say 20 seconds.

In order to verify these values selected, the liquid hold-ups were computed

Fig.3 An example of signals of void fraction obtained with axially spaced two detectors

from the A-D converted signals and compared with those obtained from the original signals for a sampling time of one hundred seconds using a slice-counter.

The calculation procedure consists of the following six steps:

- (1) The proportional constant C for calculating void fraction is determined by equation(3) from the measured output voltage V_c . Averaged value of C obtained with various calibration rods is employed.
- (2) Output voltage V_{TP} for two-phase flow is measured, from which cross-sectional mean void fraction, α , is calculated by equation(4).
- (3) The void fraction is converted into the thickness of liquid film, t_f , as

$$t_f = (1 - \sqrt{\alpha})D/2 \quad (5)$$

Through such a procedure the examples of t_f as shown in Fig.4 were yielded.

- (4) Liquid hold-up, η , and passage frequency of wave, n , are computed as shown in Fig.5.
- (5) The information on waves obtained in the step(3) are utilized to calculate the liquid hold up of disturbance wave, η_d , and its passage frequency, n_d . The details of the selection of disturbance waves from others are described later.
- (6) The thickness of base film, t_{fb} , is determined from η - and η_d - curves based on the definition made in the previous paper; i.e. t_{fb} is the y -value satisfying the following equation.

$$\eta(t_{fb}) = \eta_d(t_{fb}) + \frac{1}{2} \{1 - \eta_d(t_{fmin})\} \quad (6)$$

where minimum film thickness t_{fmin} is taken as the y -value at $\eta = 0.99$.

These calculations with six steps can successively be performed by computer.

Figure 5 is an example of n - and η -

Fig.4 Time-Varying film thickness

curves ($D = 12$ mm, $j_p = 30$ m/s, $j_i = 0.1$ m/s), and shows the definition of main parameters dealt in this data reduction of data. In the figure t_{FB} (marked by X), t_{fmin} and mean film thickness t_{fm} (by o) are designated, respectively. The value of t_{fm} is calculated from the cross-sectional mean void fraction.

The η_d -curve in Fig.5 coincides with the η -curve for $y \geq 0.2$ mm, which implies that only disturbance waves appear at a distant positions from the tube wall. η_d increases with decreasing y , and becomes nearly constant at $y = 0.12$ mm, where corresponds to the position of $y = t_{FB}$. η - and η_d -curves converge around the position of $y = t_{fm}$. This correspondence seems to be attributable to the conditions for extracting disturbance wave (as described later), one of which was assumed for the tail end of disturbance wave to be at $y = t_{fm}$.

Figure 6 indicates a comparison of the η -curves obtained by two different measuring techniques; one is the technique used herein, and the other is the traversable needle conductance probe technique. Both results are in fairly good agreement, but a tendency is noted that the η -value by the needle probe is a little greater than that of the present technique. One of the causes to produce such a difference may be that the needle conductance probe experiment exceeded a little in j_i -value.

Other causes in measuring principle can be considered: (1) The needle probe measures the depth of liquid phase with entrained bubbles, whereas the present technique gives the value by ignoring the entrained bubbles. (2) Since the interface is not spatially uniform, the needle probe is able to detect the maximum wave height existing on the circumference, but the latter is the circumferentially averaged value. The needle probe may also estimate a

Fig.5 Definition of flow parameters

greater liquid thickness than its true value due to the surface tension effect, which leads to a delay in detaching the probe from waves.

However Fig.6 in suggests that the present method is useful to clarify substantial features of the liquid film with various heights of waves. This gives a validation of the conditions for extracting disturbance wave.

Passage frequency of disturbance wave, N_d , approximately coincides with an n -value, when the n -curve remains flat as seen in Fig.5. Such a flat part of n -curve distinguishes disturbance waves from ripples on the base film.

Mean height of disturbance wave, H_{dm} is defined as y -value at $n = N_d/2$ (Fig.5), and mean separation distance of disturbance wave, L_d , is calculated as

$$L_d = u_d / N_d \quad (7)$$

In Fig.5, n takes a maximum at $y = 0.12$ mm, denoted by t_{fp} , where n_d tends to null. Since t_{fp} is very close to t_{FB} , disturbance wave is formed, as it were, on the base film. This result is consistent with the concept of the base film modelling, in which liquid phase is supposed to consist of base film, disturbance wave on the base film and droplet.

4.3 Extraction criteria for disturbance wave

In order to establish the criteria for selecting disturbance waves, the conditions characterizing the front and the tail ends of disturbance waves were examined. As can be seen in Fig.4, the wave front rises steeply. In contrast to this the surface of base film is comparatively smooth. Taking these facts into account, a criterion for determining the wave front was decided as follows.

- (a) At the wave front a gradient of the wave surface to the axial distance, dy/dL , is greater than 0.015, and then the successive three gradients measured every 1/3000 second are positive. The gradient is given as

$$dy/dL = (\Delta y / \Delta \tau) / u_d \quad (8)$$

where Δy is an increment of wave height, and $\Delta \tau$ is a reciprocal of the sampling frequency, say 1/3000 second. On the other hand the tail of disturbance wave presents a complex appearance ac-

Fig.6 Comparison between the results obtained by the present method and the needle conductance probe method

compained with surging waves, so that the following three criteria for the wave tail end were introduced and compared.

- (b-1) The distance of liquid surface from the tube wall is less than t_{fm} , and its gradient (dy/dL) is greater than -0.0015 or positive.
- (b-2) The gradient (dy/dL) is greater than -0.015 .
- (b-3) The surface distance is less than the liquid film, t_{fr} defined by the following equation, and the gradient (dy/dL) is greater than 0.0015 or positive.

$$t_{fr} = t_{fp} + (t_{fp} - t_{fmin}) \quad (9)$$

where t_{fp} is a y-value at the maximum of the n-curve and nearly equal to t_{fB} as mentioned before. Ripples appear most frequently at $y = t_{fp}$. Provided their maximum amplitude is roughly $(t_{fp} - t_{fmin})$, t_{fr} means the maximum height of the ripples.

Disturbance waves extracted by these criteria (b-1) through (b-3) along with the criterion (a) are shown in Fig.7. The results obtained by (b-1) and (b-2) indicate little difference though (b-1) may yield longer wave tails. It is obvious that the waves treated by (b-3) contain a part of ripples. Consequently the criteria (a) and (b-1) are employed in the following data processing.

In Fig.5 the broken lines of η_d and n_d are drawn using the results of extracted disturbance waves.

Fig.7 Differences of the disturbance wave signals extracted by the three combinations of the criteria (a) and (b-1), (b-2), or (b-3).

5. Experimental Results and Discussion

5.1 Liquid hold-up and passage frequency of liquid phase

Figures 8 through 10 show the distributions of liquid hold-ups, η , and passage frequencies of liquid phase, n , against the distance, y , when superficial velocities j_g and j_l , and tube diameter D are taken as parameters. The figures also indicate η_d -, n_d -curves, mean film thickness (marked by $\circ$), and base film thickness ($\times$).

It is pointed out from the figures that mean film thickness corresponds to the position of $\eta = 0.2$. According to the previous report on the investigation of the ripple regime in annular flow, mean film thickness for this regime is the position of $\eta = 0.35$. Such a difference in the relationships between mean film thickness and their positions on η -curves depends on whether the disturbance wave exists or not. Thus the magnitude of the η -value specified by mean film thickness may be useful for the discrimination of the existence of disturbance wave. Base film thickness corresponds to $\eta = 0.6$.

Figures 9 and 10 reveal that η -curve and the maximum of n shift to the tube wall with a decreasing tube diameter from 26 to 12 mm and then turn to the tube center. As would be expected from this fact, in general η and n are complicatedly linked with D , j_g and j_l .

The figures suggest that disturbance waves are reasonably selected because n_d starts to decrease monotonously with a decreasing y nearly at the turning point of n -curve from the flat zone to the drastically increasing zone.

5.2 Velocity of disturbance wave

Data points are plotted by the symbols tabulated in Table 2, and some are those of an experiment made using the needle conductance probe technique with a tube of 25 mm in diameter. Figure 11 shows the effect of tube diameter on the velocity of disturbance wave u_d . It should be noticed that u_d

Fig.8 Effect of j_g on n - and η -curves

increases with a decreasing D and then decreases after taking a maximum around a diameter of 12 mm.

In the figure the correlation by Shearer and Hall-Taylor is also expressed by broken lines. However, the smallest size of test tube used by Shearer and Hall-Taylor was 15.9 mm in diameter, so that the region below this limitation of diameter is drawn by dotted lines.

5.3 Mean passage frequency of disturbance wave

Figure 12 shows the effect of tube diameter on mean passage frequency of disturbance wave N_d . For $j_l = 0.04$ m/s there

j_l , m/s \ D , mm	8	12	18	25	26
0.04	◇	○	□	△	▽
0.06	◆	●	■	▲	▼
0.1	◇	○	□	△	▽
0.14	◆	●	■	▲	▼

Table 2 Symbols used in Figs.11 through 16

.....; Shearer & Hall-Taylor et al.

Fig.11 Disturbance wave velocity

Fig.9 Effect of D on n - and η -curves

Fig.10 Effect of D on n - and η -curves

is the tendency as in the case of u_d has a maximum at $D = 10\text{--}15\text{ mm}$. For greater values of j_i , N_d decreases monotonously with D . A comparison of the present results with the correlation of Shearer and Hall-Taylor is given in the figure. The correlation predicts lower values than the experiment for $j_g = 20\text{ m/s}$. With this exception the agreement is excellent.

5.4 Mean separation distance between disturbance waves

Mean separation distance between disturbance waves L_d was calculated by equation(8). In order to examine the magnitude of deviation of every separation distance from the mean value, some data on a test tube of 8 mm were analyzed as follows.

Time differences between successive two waves, τ_{id} , were measured from the void data recorded on oscillograph paper as shown in Fig.3. About two hundred L_d -values were obtained by multiplying these time differences τ_{id} by u_d . Such L_d -values are expressed by a log-normal distribution, and its standard deviation becomes less with j_g ; i.e. 50 % at $j_g = 20\text{ m/s}$ and $j_i = 0.1\text{ m/s}$, and 20 % at $j_g = 50\text{ m/s}$ and $j_i = 0.1\text{ m/s}$. The effect of D on L_d is shown in Fig.13. In general L_d increases with D . The dependency of L_d on j_i becomes clear with a decreasing j_g . Especially it is pronounced at $D = 8\text{ mm}$.

-----; Shearer & Hall-Taylor et al.

Fig.12 Mean frequency of disturbance wave

-----; Yagi et al.

-----; Anderson et al.

Fig.13 Mean separation distance between disturbance waves

Fig.14 Mean liquid film thickness

Fig.15 Base film thickness

Fig.16 Mean height of disturbance wave

5.5 Mean film thickness

Figure 14 shows the effect of D on mean film thickness t_{fm} . In most cases besides $j_0 = 20$ m/s, t_{fm} takes a minimum at $D = 10$ –15 mm.

In the figure chain lines indicate correlation for hold-up by Yagi and Sasaki and broken lines the analysis by Anderson and Mantzouranis. Yagi and Sasaki made experiment on hold-up with four tubes of different diameters (8, 10.25, 12.5, and 17.5 mm), and concluded that the difference of the tube diameters had no effect on the hold-up. Then the flow regimes tested were froth and annular flows. On the other hand Anderson and Mantzouranis proposed an analysis for determining liquid film thickness, and presented a chart for its calculation. Reading errors of the chart are unavoidable to some extent. Therefore the calculated broken lines do not vary in a systematic way. It is noted that these two predictions produce a monotonous change of t_{fm} with D in contrast with the experimental results presenting a minimum.

5.6 Base film thickness

Figure 15 shows the effect of D on base film thickness t_{fb} . Since the magnitude of t_{fb} is 60–70 % of t_{fm} , its general tendency is similar to that of t_{fm} . The effect of j_0 on t_{fb} -curves is systematic and becomes less with j_0 .

5.7 Mean height of disturbance wave

The change of mean height of disturbance wave H_{am} due to D is not so simple as seen in Fig.16, but the order of magnitude in H_{am} decreases clearly with j_0 . Velocity of disturbance wave is remarkably lower than the gas velocity, say about 10 % of j_0 in Fig.11. While disturbance wave has a steeply raised crest. Therefore a drag force on the disturbance wave due to gas stream can play a major part in the force balance of the interface. From this expectation, the opening ratio, β , at the crest of disturbance wave is written in the figure. Data points indicate greater opening ratio with j_0 , ranging from 0.5 to 0.9.

Based on the present experimental data the correlations for various parameters have been derived and made available in the other report.

6. Conclusions

A computer-aided-data-processing was developed for investigating into the flow characteristics of liquid film and waves in annular flow; various flow parameters can be processed by computer without laborious treatment after recording the information of void fraction on magnetic tape. The effects of tube diameter were examined on flow parameters such as velocity and passage frequency of disturbance wave, mean film thickness, base film thickness, etc. The results of obtained are summarized as follows:

- (1) Criteria for extracting disturbance waves from base film using void signals were established, with which their liquid hold-up η_d and passage

frequency n_d were determined.

- (2) The criteria are provided on both the front and tail ends of disturbance wave as follows.
 - (a) As for the front end, a gradient of the wave surface to the axial distance dy/dL is greater than 0.015. In addition to this the successive three gradients measured every 1/3000 second are positive.
 - (b) The tail end is determined such as to satisfy the condition that the distance of liquid surface from the tube wall is less than t_{fm} , and its gradient dy/dL is greater than -0.0015 or positive.
 A comparison was made between the η -curves obtained by two different methods; i.e. the present and the needle conductance ones. Thus the criteria proposed herein were verified.
- (3) It was made clear that the velocity of disturbance wave plotted against tube diameter has a maximum. Under some combinations of superficial gas and liquid velocities, passage frequency of disturbance wave also has a maximum. Such tendencies were confirmed generally to coincide with those predicted by the correlations of Shearer and Hall-Taylor.
- (4) Thicknesses of mean and base film have a minimum at the tube diameters of 10 to 15 mm and at higher gas velocities, say greater than 30 m/s.

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