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Quantitative Characterizations of Phasic Structure Developments by Local Measurement Methods in Two-Phase Flow

by

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Abstract

An experimental study on the internal structure of an adiabatic two-phase flow has been carried out in a 25.4 mm ID pipe. The local void fraction and interfacial area concentration were measured by a double-sensor probe. The flow structure development was visualized by measuring the radial distribution of these two parameters at three axial locations (L/D = 12, 62, and 112).. A more detailed study on the fully developed flow structure was conducted at L/D = 120. The interfacial structure were measured by the double- and four-sensor probes. A bubbly-to-=slug transition region was defined according to the local data. The area-averaged void fraction measurements were given by a gamma densitometer. Other parameters such as the Taylor bubble film thickness, bubble length and slug unit length in slug flow were measured by a film probe. The redundant measurements were made to calibrate the local probe measurements. The quantitative representation of the phasic structure can then be used for modeling.

1. Introduction

The internal structure of a two-phase mixture affects the mass, momentum and energy transfer between the two phases as well as those between the mixture and the flow channel. Dukler and Taitel (1) have summarized various observations on flow patterns and presented in form of flow regime maps for different channel shape and orientations. However, this is only a qualitative representation of the phase structure in variety of flow conditions. In terms of modeling the interfacial transfer, a more elaborated quantitative representation is necessary to model the coupling between the gs and liquid phases in the flow field (2). The interfacial area concentration (IAC) is regarded as the geometric factor of the interfacial transfer (2,3). A closure relationship must be developed to give a quantitative prediction of such factor. In this paper, we present the measurement techniques used for measuring various parameters that are important for modeling the interfaces in the dispersed bubbly flow and slug flow regimes.

Acquiring the necessary data is the first step toward modeling the interfacial geometry. The recent progress in the local multiple-sensor probe method (3,4,5) has made the measurement of the local IAC possible. It has been proven to be a reliable and simple tool for local IAC measurement . The local probe measurements can be used to reconstruct the interfacial area field in the following way. first, it is used to map the radial distribution of the void fraction and IAC. Secondly, the flow structure development can be visualized by conducting the local measurement at different axial locations. There are two types of multiple-sensor probes namely, double-sensor and four-sensor probe. The double-sensor probe has a much smaller cross-section and used for measuring the small bubble IAC. For large bubbles such as the Taylor bubbles, the four-sensor probe can be used.

The flow structure development data is of importance to modeling the dynamic change of the interfacial structure in developing or transient two-phase flow. An interfacial area concentration interfacial structure in developing or transient two-phase flow. An interfacial area concentration transport equation is proposed by Ishii et al. (6). A practical form of one-dimensional model is given as

$$\frac{\partial}{\partial T}\langle a_i\rangle + \frac{\partial}{\partial z}\langle a_i\rangle\, \overline{v_{iz}} = \langle\phi_{dis}\rangle - \langle\phi_{col}\rangle + \langle\phi_{ph}\rangle + \langle\phi_w\rangle \tag{1}$$

where ϕ_{dis}, ϕ_{col}, ϕ_{ph}, and ϕ_w, are the source due to disintegration of fluid particles, the sink due to coalescence of fluid particles, the source/sink due to phase change, and the source/sink due to phase change at the wall, respectively. The angle brackets represent the area average of the parameters. Noted that the phase change terms, ϕ_{ph} and ϕ_w, can be either source or sink depending on the thermodynamic condition of the flow. All the terms on the right-hand-side must be determined by constitutive relations that model the mechanism of the interaction between the fluid particles in the flow fields and the phase change processes.

In adiabatic flow, the source term of phase change is set to zero. The only source or sink for interfacial area is due to coalescence or due to breakage of the bubbles. These processes are also dependent on the flow regimes. For instance, the transition from dispersed bubbly flow to slug flow requires that the small bubbles conglomerate into a large Taylor bubble. Hence, bubble collision is a very important process for the transient. On the other hand, in the slug flow regime, the coalescence precess is dominated by the wake entrainment behind the Taylor bubbles. The initial condition of the flow is also important for modeling the source and sink. The flow development study can help us to determine some of these conditions. Furthermore, local data can provide more information on the flow regime transitions. and the effect of the initial condition on the flow structure developments in different regimes.

The characteristic flow structure in a fully developed two-phase flow is also important for modeling the transport equation because it calibrates the possible stable phasic structure, to which the transient flow evolves. More elaborated measurements have been conducted at the fully developed region. A gamma densitometer is used for measuring the area-averaged void fraction. A film probe is used to measure the Taylor bubble film thickness, bubble length and slug unit length. The internal structure can be visualized more fully in by these measurements. The details of these measurement techniques will be discussed in later section.

2. Interfacial Area Model

The IAC is important to the mechanistic modeling of the interfacial transfer. The fist systematic discussion of quantifying the interfacial area concentration has been given by Ishii and Mishima [7]. The parameters to determine the size of IAC is given in Fig. 1. It illustrates the expected interfacial structure in bubbly flow and slug flow regimes.

In dispersed bubbly flow, the gas phase exists in a form of small bubbles. The IAC of the two-phase mixture can be expressed in term of the Sauter mean diameter as [7]

$$a_i = \frac{6\alpha}{D_{Sm}} \tag{2}$$

Since the local double probe method can measure the IAC directly, the Sauter mean diameter Dsm can be back calculated. However, there is another way to obtain the Dsm if the bubble size distribution is known. The definition of the Sauter mean diameter is given by

$$D_{Sm} = \frac{\int D^3 f(D_d)\, dD_d}{\int D^2 f(D_d)\, dD_d} \tag{3}$$

where $f(D_d)$ is the bubble size distribution function. This distribution can be obtained from the chord length distribution measured by the double-sensor probe. The detail mathematical relationship is given in next section.

In slug flow regime, the gas phase distributes among two types of bubbles as shown in Fig. 1b. The Taylor bubble is the most dominant feature in the flow field. It is followed by a liquid slug region which contains a large amount of small bubbles. The combined flow field is called a slug unit. The IAC can be estimated from the size of the Taylor bubble and Sauter mean diameter of the small bubbles. From a simple geometric consideration, the IAC within the slug unit is given as [7]

$$a_i = \frac{1}{D_b}\left(\frac{4 + D_b/L_b}{1 - D_b/6L_b}\right)\left(\frac{\alpha - \alpha_{gs}}{1 - \alpha_{gs}}\right) + \frac{6\alpha_{gs}}{D_{Sm}}\left(\frac{1 - \alpha}{1 - \alpha_{gs}}\right) \tag{4}$$

where D_b, L_b, and α_{gs} are the bubble diameter, bubble length, and void fraction in the liquid slug. The first two parameters can be measured directly by the film probe. The last parameter α_{gs} can be obtained by segregating the Taylor bubble portion from the total void fraction.

There are not many experimental data or correlation concerning the stable Taylor bubble length L_b. Mishima and Ishii [8] proposed a flow model for falling film to predict the averaged void fraction and length of a Taylor bubble. The film reaches its terminal velocity when the gravity force is balanced by the wall friction. Then the Taylor bubble reaches its maximum stable length. The correlation for the bubble length L_b is given as [8]

$$\sqrt{\frac{2L_b}{D}} = \frac{j}{V_b} + 0.75\left(\frac{\Delta\rho g D^3}{\rho i\, {}^{v}i^2}\right)^{1/18} \tag{5}$$

where V_b is defined as $V_b = \sqrt{\Delta\rho g D/\rho_1}$,

ρ_1, ρ_g, $\Delta\rho$, v_1, D, and g are the liquid phase density, gas phase density, liquid-gas density difference, liquid viscosity, pipe diameter, and gravitational acceleration respectively. The above correlation shows that the bubble-length is a weak function of liquid viscosity and it increases with the mixture volumetric flux. Dealing with the same model, the averaged void fraction can be obtained by integrating the local area-averaged void fraction through the length L_b and resulting expression is given as [8]

$$\alpha_m = 1 - 0.813\left(\frac{0.2(1 - \sqrt{\rho / \rho j} + 0.35V_b}{J + 0.75V_b(\Delta\rho g D^3 / \rho_1 v_1^2)^{1/18}}\right) \quad (6)$$

The averaged film thick ness of a Taylor bubble can be calculated from the average void fraction by

$$\frac{\delta}{D} = \frac{1}{2}(1 - \sqrt{\alpha_m}) \quad (7)$$

where α_m is the mean void fraction defined in Eq (6) and δ is the averaged film thickness of the Taylor bubble. The Nusselt's laminar falling film model is used by Jayanti and Hewitt [9] to predict the film thickness in slug flow regime. The film thickness is given by

$$\delta = [\frac{3V_{gJ}\, D\mu_i}{4g\Delta\rho}]^{1/3} \quad (8)$$

These correlations will be examined with the experimental results. The parameters Dsm, L_b, and δ can be measured by the double-sensor and film probes. The average IAC can be computed from these parameters and used to compare with the multiple-sensor measurements.

3. EXPERIMENTAL APPARATUS

The experiments are carried out in an air water system. The test-section is made of a 3750 mm long with 25.4 mm ID Lucite tube. Forced flow of water is provided by a centrifugal pump. It can deliver the liquid flow rate up to 3.7 ms^{-1} in this test -section. The pump heating rises the water temperature by 2°C per hour. In order to keep the water temperature constant at 23±2°C, a heat exchanger is installed in the reservoir tank. Air is injected through a porous tube located in the mixing chamber. The bubbles generated by this injector are in the order of 4 to 5 mm. The air flow is driven by the back pressure of a large storage tank which is pressurized to 120 psig. This air tank can provide air flow rate up to 3.5 ms^{-1} (in 25.4 mm ID pipe) and maintains a constant flow rate for a long period of experiment. This air-water system gives the adiabatic two-phase flow condition spanned over bubbly to churn-turbulent flow regime. The liquid flow rate is measured on-line by a orifice flow meter. The air flow rate is measured by a rotometer.

The local instrumentation is designed to measure specific parameters which appear in the interfacial area model. some of the measurements are redundant and can be used to cross-calibrate the experimental results. Instrumentation for the experiment are described in detail in the following sub-sections.

3.1 Local IAC Measurements

The resistivity probe dis a rather simple device. The sensor of the probe is made of Platinum with 13% Rhodium wire (dia. 0.12 mm). It makes electrical contact with the surrounding medium. The electrical output is sensitive to the change of resistivity at a local point. It is primarily used as a phase identifier. Hence, interface can be marked by the rising and falling edge of the signal. Two types of multiple-sensor probes. The probe is mounted on a special flange. the end of the probe holder is attached to a mechanical traverser. The probe can be moved back and forth in the radial direction. Hence, the radial distribution of void fraction can be mapped out by successive measurements. With two closely spaced sensors, the probe can be used to measure the interfacial velocity. It has been shown mathematically that the IAC equals to the harmonic mean of the interfacial velocity [3]. The theoretical base of this measurement technique is given by Kataoka et al. [3], and the local time-averaged IAC is given by

$$\overline{a_i^t} = \overline{\frac{1}{|n_i \cdot v_i|}} \tag{9}$$

A four-sensor probe (or called three double-sensor probe) is proposed [3,4] to measure the interfacial velocity in three independent directions. The probe size must be small relative to the size of the interface. However, the sensor distance cannot be made too due to engineering problems. In order to obtain a reasonable time resolution, the sensors are separated by 3 to 4 mm. Hence, this probe can only be used for measuring large bubble, for example, Taylor bubbles in slug flow. The applicability of the four-sensor probe has been determined by Revankar and Ishii [4]. They compared the local data of the probe measurements with the photographic studies and the agreement was good.

As explained above, the four-sensor probe if too large for measuring the small bubble velocity. for these cases. a miniaturized double-sensor probe is used for measuring the axial velocity of small bubble. In order to relate this axial velocity to the interfacial velocity, the statistical characteristics of small bubbles lateral motion must be postulated. Since bubbles move mainly in the axial direction, the average lateral velocity must be very small. The fluctuating motion of bubbles upon the main flow is due to liquid phase turbulence which is near isotropic at the core region. Hence, fluctuation of the bubble velocity may be approximated as isotropic. With these assumptions, the local time-averaged IAC can be expressed as [3,5]
where N_b, v_{szj}, Θ_0 are the number of bubbles per second, measured axial bubble velocity, and the

$$\overline{a}_i^t = \frac{4N_b(1\overline{/v_{szj}})}{1 - \cot\frac{\Theta_0}{2} \, In(\cos\frac{\Theta_0}{2}) - \tan\frac{\Theta_0}{2} \, In(\sin\frac{\Theta_0}{2})} \tag{10}$$

maximum angle of deviation from the axial flow in terms of velocity. The value of Θ_0 can be estimated &om the measured values of statistical parameters of interfacial velocity as given by Kataoha et al. [3], thus

$$\frac{\sin\Theta_0}{2\Theta_0} = \frac{1 + \sigma_z^2/|\bar{v}_{iz}|^2}{1 + 3\sigma_z^2/|\bar{v}_{iz}|^2} \qquad (11)$$

where σ_z is the standard deviation of v_{iz}. Local multiple-sensor probe methods have been briefly discussed here. The details of the measurement method, probe design and signal processing can be found in references [3], [4], [5] and [lO].

Other then the IAC measurement, the double sensor can also give the chord length measurement of the small bubbles. The chord length distribution can then be transformed into the bubble size distribution. The mathematical derivation of the transformation matrix has been studied by Clark and Turton [Il], assuming that the bubbles are in perfect spherical shape. For a specific bubble size of diameter D_d, the probability of the probe cutting through the bubble at the chord length y is given [11]by

$$P(y|D_d) = \frac{2y}{D_d^2} \qquad (12)$$

The maximum chord length of a given size is the diameter of the bubble. If the size distribution is $f(D_d)$, the probability of having a chord lengthy is given by

$$p(y) = \int_y^{D_{max}} p(y|D_d)f(D_d)dD_d \qquad (13)$$

where D_{max} is the maximum possible bubble diameter. The lower limit of the integration is set at y because the bubble at least has the size y in order to have a contribution. Let's denote the approximated chord length distribution by w_i

$$w_i = \int_y^{y_{i+1}} p(y)dy \qquad (15)$$

Putting it in a form of matrix, the chord length distribution is given by

$$[w_i] = [C_{ij}][f_j]$$

$$\text{where} \qquad C_{ij} = \int_{y_i}^{y_i+1} p(y|D_{dj})dy, \qquad (15)$$

$$\text{and} \qquad f_j = f(D_{dj})\Delta Dd.$$

3.2 Averaged Void Fraction Measurements

The gamma densitometer is a non-intrusive method for measuring the void fraction in phase flow. A one-shot type device for measuring the area-averaged void fraction has been studied by Eberle et al. [I2] among others. A collimator is put in front of the source to shape it into a I mmx 26 mm sheet of radiation. It illuminates a thin slice of the pipe cross-section. The densitometer is located at L/D = 100. The test-section is sandwiched between two pieces of 0.75 inch thick stainless steel blocks used as the biological shield. The detector is placed in a short distance from the test-section to catch the transmitted photons. The void fraction can be measured accurately by careful use of the densitometer. The source is an Am^{241}, and the gamma emission line peaks at 59.5 keV. The source strength is 0.387 curies to deliver a enough count rate to keep the statistical error minimal. The detection system is a $N_aI(Tl)$ crystal detector used in conjunction with the ORTEC amplifier TSCA 590A and ORTEC Timer Counter 996.

The counting time is set to be 1 minute. The reason for the long duration of measurement is that the flow field in slug or chum-turbulent regime is intermittent between the liquid slugs and Taylor bubbles. A long observation time is needed to average out these macroscopic fluctuation of the flow field. The count of photon is in the order of 50,000 and the statistical error is about 0.4% for each measurements. However, to ensure the dynamic fluctuation does not affect our measurement, five measurements were made for each flow condition. The void fraction measurements has been calibrated against the pressure drop measurements [12], and the agreement is good to within 10% at low flow. In addition to the long counting time, a short count time with recycle time of 10 ms is also taken to obtain the time trace of the void fraction. This measurements are used to calibrate the film probe.

3.3 Film Thickness Measurement

The film thickness can be measured by the film probe. The voltage output is directly proportional to the film thickness. The system that used in this experiment was developed by Wu and Ishii [131]. The probe is made of two thin needles which are insulated at the upper half of the probe. The diameter of the needle is 0.12 mm. The hydrodynamic jump caused by the needle is kept to minimal. The two needles are installed at the diameter of the pipe. They are aligned in the flow direction and separated by 5 mm. An AC current passes from the wire into the liquid film. A circuit is built for sensing the current change due to the film thickness and converts the signal into a DC voltage output. A calibration study has been conducted by Wu et al. [13]. The film thickness as low as 0.5 mm has been calibrated. For thinner liquid film, a flash mounted probe may be preferable. An on-line calibration of the probe is given by the short pulsing gamma ray measurement. The results are shown in Fig. 2. Most of the data are within 15% of agreement. Two probes are built in the test section. They are separated by 67.5 mm. The Taylor bubble velocity can be measured by cross correlating the two signals. Then the bubble and slug unit length can be computed from these measurements.

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

The experimental conditions are summarized in Table 1. Two separate sets of experiments were conducted on the air-water system. These are the flow structure development study and the interfacial structure study in the fully or near fully developed flow. The multiple-sensor probe has been used extensively in these experiments because the local profile of void fraction, IAC, interfacial velocity, bubble frequency, and chord length can he measured simultaneously. other instrumentation such as the gamma densitometer and film probe are also used for studying the fully developed interfacial structure.

4.1 Flow Structure Development Studies

In the flow structure development study, the double sensor probe measurements are conducted at three axial locations (L/D= 12, 62, 112). The flow structure development can be visualized by these local measurements. The two most important parameters for the interfacial structure are the void fraction and IAC. Two groups of data are presented in this section.

The effect of j_g on the flow structure development is presented in Fig 3. The liquid velocity j_l, is kept constant at 0.62 ms^{-1} while j_g is increased from 0.09 to 0.96 ms^{-1}. The void fraction increases with j_g while this is not always true for the IAC. For $j_g \leq 0.3$ ms^{-1}, the flow is in bubbly flow regime. The number of bubbles in the two-phase mixture increases with j_g, hence, the IAC increases with the gas flux. Furthermore, the IAC has a similar distribution as the void fraction. At higher gas flux of 0.69 and 0.96 ms^{-1}, the IAC contribution from small bubbles does not increase with j_g. The average IAC is smaller for the second case although the second j_g almost 40% higher than the first one. It is because the increases in j_g is mostly absorbed into the Taylor bubbles which grow larger in the later case of gas flow rate.
Visualization of the interfacial structure development is provided in consecutive displays of local profiles at the three axial locations in Fig. 3 (a to c). For j_l 0.3 ms^{-1}, both the void fraction and IAC show a wall peaking distribution at the entrance region and they change to core peaking distribution toward L/D = 112. Taylor bubbles are found in the mid-section. They are relatively small and few in number. Therefore, they have no significant effect on the IAC profiles of small bubbles. On the other hand, for j_l, = 0.69 & 0.96 ms^{-1}, the flow is in slug flow regime. Taylor bubbles are found right at the entrance region (L/D=12). The IAC and void fraction distributions do not have any resemblance to each other because the void fraction includes the contribution from the Taylor bubbles as well. For j_l = 0.69 ms^{-1}, it has the largest IAC in this group. The IAC shows a wall peaking distribution while the void fraction has a core peaking distribution. For j_l1 = 0.96 ms^{-1}, the IAC wall peaking profile has been established right at the entrance. It has no significant change along all three axial locations. The corresponding void fraction has a core peaking distribution at the entrance and it becomes more evenly distributed at L/D = 112. In both cases, the area-averaged IAC

decreases at L/D = 112.

Fig. 4 presents a group of data with j_g remaining constant at 0.29 ms^{-1} while j_l increases from 0.3 to 3.0 ms^{-1}. The effect of liquid velocity on the distribution can be examined. For j_l = 0.3 ms^{-1} the void fraction and IAC distributions develop in different way. The void fraction changes from a wall peaking to a parabolic distribution while the IAC develops into a wall peaking distribution. The average IAC decreases significantly at L/D = 112. In slug flow regime, the IAC has a wall peaking distribution while the void fraction has a core peaking distribution. For $j_l \geq 1.0$ ms^{-1}, the flow is in bubbly flow regime. There is no significant change of the void fraction and IAC distributions along the axial length. The wall peaking distribution is not found in j_l = 3.0 ms^{-1}. However, a small intermediate peaking is found at L/D≥62.

For the flow structure in fully developed region, other set of experiments was conducted at L/D = 120. The double-sensor probe was mainly used and four-sensor probe was applied only if it was necessary. A group of data is presented in Fig 5. In this figure, j_g is held constant at 1.0 ms^{-1} while j_l is changed from 0.0 to 1.0 ms. The radial distributions of void faction are similar at all liquid flux. They have uniform distributions at the core region. The local IAC measured by the double-sensor probe and by the four-sensor are presented in Fig. 5.b. Saddle shape distributions are found in both types of IAC. This shape of distribution for Taylor bubbles is due to the geometric orientation of the interfaces while, for small bubbles, it is due to bubble number density wall peaking distribution.

From the local data, it can be seen that the bubbly-to-slug (BTS) transition spans over a range of void fraction in contrast to a clear cut boundary presented in traditional flow regime map. To find such a region, it is necessary to determine when Taylor bubbles start to form and when they become significant contributors to the void fraction. In the void measurements, bubbles can be separated into either a Taylor bubble or a small bubble based on the double-sensor probe signals.
Thus the void fraction for each category can be obtained separately. The results are presented in Fig. 6. The transition region starts when Taylor bubbles form but they are relatively small and few in number. The portion of void fraction from Taylor bubbles is only a few percent of the total void fraction. This transition region is found at $0.16 \leq \langle\alpha\rangle \leq 0.3$. At $\langle\alpha\rangle = 0.3$, the percentage of void fraction from the Taylor bubbles jumps to over 50% of the total void. The above observations apply to the conditions specified, however, at other flow rates the transition region may change.

4.2 The Area Averaged Measurements

The axial symmetry of the flow structure is not always realized in a vertical test-section. The gamma densitometer does have the advantage of measuring the area-averaged void fraction such that the flow structure asymmetry does not significantly affect the result. The local data measured by double-sensor probe are integrated over the cross-sectional area to obtain the area-averaged void fraction. In comparison with the gamma measurements, these data show a reasonably good agreement within 20%, and the results are presented in Fig. 7.

The average void fraction of a given condition can be predicted by the drift flux correlation. To analyze the average relative velocity, Zuber and Findlay [14] proposed the following expression

$$\frac{j_g}{\alpha} = C_0 j + V_g j \quad (16)$$

where C_0 is the distribution factor and V_{gj}, is the mean local drift velocity. These two parameters can be obtained by a linear plot j_g/α against j when C_0 and V_{gj}, are constant. For slug flow regime, the drift velocity is given by

$$V_{gj} = 0.35\sqrt{gD} \quad (17)$$

The area-averaged void fraction used in this plot is the result from the gamma densitometer measurement. The drift flux presentation is shown in Fig 8. The distribution coefficient C_0 is 1.3 and the drift velocity is 0.17 ms^{-1}. For a distribution factor greater than 1.0, it implies a core peaking distribution of the void fraction. This is in agreement with the local observation.
The alternative way to obtain the average IAC is using the Sauter mean diameter D_{Sm}, film thickness δ, bubble length L_b, and slug unit length L_u , obtained from the experiments. The Sauter mean diameters are computed from the chord length distribution as mentioned in section 4.1. The local flh of small bubbles versus void fraction is presented in Fig. 9. The experimental results show that D_5rn ranges from 3.0 to 5.0 mm. The largest scattering of the bubble size is located at void fraction between 0.2 to 0.6. This may be caused by the flow structure change. For local void fraction greater 0.6, the bubble size becomes smaller and less scattered and D~ ranges from 3.6 to 4.2 mm.

The averaged film thickness of Taylor bubble is measured by the film probe. For each data point, over 750 Taylor bubbles are sampled in order to obtain a correct statistical mean. The bubble length and slug unit length are also measured simultaneously. The film thickness data are presented in Fig. 10. The two lines are obtained from the correlations by Mishima et al. [8] and Jayanti et al. [9]. For the fully grown Taylor bubble, the film thickness falls between the predictions of these two correlations. The predictions from the correlations do not have good agreement with the data beyond a correct order of magnitude. Furthermore, they show very weak dependence on the liquid velocity while the measured film thickness increases with the liquid velocity for I' between 0.0 to 1.0 mso'.

The Taylor bubble length and the slug unit length are also measured simultaneously with the film thickness measurements. The results of bubble length are presented in Fig 11. The area bounded by the solid lines are the predictions by Mishima and Ishii's [81 correlation. The model film thickness is the minimum thickness at the tail end of the Taylor bubble. Thus the data are expected to he higher than the predictions. The effect of the liquid flux on the slug length appears to be the opposite of the model predictions. These results indicate that the existing models are not very satisfactory in predicting the details of the interfacial structure. The trend of Lu is similar to the Taylor bubble lengths. The superficial liquid velocity has a strong effect on La.
The data collapse on a single line if normalized length is plotted against the area- averaged void fraction in a semilog graph (see Fig 12). The correlation obtained as

$$\log(\frac{Lc}{D}) = 6.6<\alpha> -0.3 \qquad (18)$$

This correlation is strictly empirical and bears no implication on the physical process. However, it does show that the Taylor bubble length is a strong function of void fraction instead of the mixture velocity. This holds true at least for j_l 1.0 ms^{-1} according to our data. Furthermore, Grifiith and Wallis'[15] 1.0 inch pipe data can be also fitted onto the same line at lower void fraction range. A better understanding of the liquid flow around the Taylor bubble is necessary for physically modeling the stable bubble length ad the film thickness.

4.3 Area-Averaged IAC at the Fully Developed Region

An alternative way to obtain the IAC is using the parameters measured in previous subsection. The data for film thickness and Sauter mean diameter are extrapolated from the measured results. The computed IAC curves is present in Fig. 13 with the total IAC measured by the multiple-sensor probe methods (including double and four-sensor probe). The curve marked with an A is computed directly from the measured result. Two places in the curve show rapid transitions. The first one is due to the jump in the percentage of Taylor-bubble void fraction and the second one is due to the jump in the small bubble Sauter mean diameter D_{sm}.

The line marked `PIJRE BUBBLY' is the IAC if the flow remains in bubbly flow. The D_{Sm} is set to be 4.5 mm for computing the average IAC. For j_l = 1.0 ms^{-1}, the flow remains essentially in the bubbly flow regime over the transition region but Taylor bubbles are also detected in the double probe measurements. However, the number and the size of the Taylor bubbles are insignificant to the overall void fraction and IAC. The other line marked `PURE SLUG' represents the IAC computed as if there are only Taylor bubbles in the flow. It shows a significantly lower value for IAC due to the lack of small bubble contributions.

In summary, the total IAC can be computed from the bubble length, film thickness, and Sauter mean diameter. The small bubble size and its concentration have a strongest effect on the overall IAC both in bubbly flow and slug flow regimes. Thus the D_{Sm} for small bubbles is a very important parameter. However, it is also necessary to know the Taylor bubble length and the slug unit length in order to predict the correct ratio of the void fraction distributing amount the two types of bubbles. For developing a closure relation for IAC, it is necessary to improve our understanding of the physics in the slug flow regime.

5. CONCLUSION

The multiple-sensor probe can measure the local void fraction and IAC. The interfacial structure development can be visualized by conducting the measurements at three axial locations (L/D = 12,62 and 112). The distribution and redistribution process in developing flow are very much related to the flow regimes and regime transitions. There is a certain range for the bubbly-to-slug transition in terms of the void fraction. Larger Taylor bubbles start to form but they are insignificant in number and size. At the BTS transition boundary $<a> = 0.3$, Taylor bubble grows in number and sizes. It contains roughly 50% of the gas volume and 20% of the overall IAC at this point.

The gamma densitometer is a useful instrument for measuring the area-averaged void fraction. The experimental result is used for the drift flux presentation to find out the distribution factor C_0 and drift velocity V_{gj}. The values of C_0 and V_{gj}, are found to be 1.3 and 0.17 ms^{-1}, respectively, which are the typical value for slug flow regime.

The film thickness, bubble length, and slug unit length of the Taylor bubbles are measured by the film probe. These are the parameters needed for computing the average IAC based on the global geometrical model. The computed result is in good agreements with the IAC measured by the multiple-sensor probe. The film thickness does not affect significantly the IAC prediction if it is small relative to the pipe size. The bubble and slug unit length are important for predicting void distribution among the two types of bubbles. However, a significant portion of the IAC in slug flow is due to the small bubbles in the liquid slug. Hence, an accurate correlation for the Sauter diameter is necessary for predicting IAC both in bubbly and slug flow regime.

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