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Void Fractions in U-Bends of a Serpentine Tube

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Abstract: Void fractions of air-water two-phase flows in a serpentine tube consisting of vertical U-bends and circular straight pipes were measured by using the quick-closing valve method. The pipe diameter, D, and the bend radius, R, of curvature were 20 mm, so that the bend ratio, R/D, was unity. The lengths of the straight pipes, L, were 1500 mm and L/D = 75. The main conclusions obtained are as follows: (1) the void fractions in the upward flow are accurately evaluated using the drift-flux model with the distribution parameter, C_0, and drift velocity, V_{Gj}, for developed co-current flows, and Usui's correlation agrees well with the void fractions of downward annular flows, (2) the effect of the serpentine tube arrangement on the downward flow is remarkable in the slug flow due to a large difference between the void fractions of the upward and downward slug flows, (3) the bend void fractions can be estimated by simply averaging the void fractions in the straight pipes, and (4) the bend void fractions are well evaluated by averaging the void fractions calculated by the correlations for the upward and downward pipe flows.
Keywords: slug flow, annular flow, drift-flux model, return bend

1. Introduction

A serpentine tube, which consists of straight pipes connected to 180° return bends (U-bends), is widely used in practical application such as the tube coils of process fired heaters in refineries, petrochemical plants and so on. Gas-liquid two-phase flows are formed in the tube coils and their flow patterns are either slug flow, churn flow or annular flow under the nominal operating condition. The upward flow in a vertical pipe of the serpentine tube changes its flow direction from upward to downward due to the top U-bend (the inverted U-bend), and the flow goes down in the downstream vertical pipe toward the bottom U-bend. Then, the bottom U-bend changes the flow direction from downward to upward. The characteristics of the two-phase flow thus vary in the axial direction, and therefore, obtaining knowledge on the void fractions in each section is of great importance for designing serpentine tube coils and selecting monitoring points for tube temperature.

Oshinowo and Charles (1974a) observed flow patterns in a serpentine tube of the pipe diameter D = 25 mm with U-bends of R/D = 3 and 6, where R is the bend radius of curvature. They classified the flow patterns into several flow regimes and developed a graphical flow pattern correlation for upward and downward flows. Oshinowo and Charles (1974b) measured the void fractions of upward and downward flows in the straight pipes of the serpentine tube by trapping the gas and liquid inside the pipes using quick-closing valves. They showed that the void fraction in the straight pipe was hardly influenced by R/D. Usui et al. (1983) obtained the area-averaged void fractions of downward bubbly and plug flows passing through an inverted U-bend of D = 24 mm and R/D = 4 by integrating local void fractions measured by using an electrical-resistance needle probe. They pointed out that the drift-flux model (Zuber and Findlay, 1965) with available correlations of the distribution parameter and the drift velocity for developed upward flows (Wallis, 1969) and downward flows (Samuel et al., 1976) cannot accurately evaluate the void fraction in the bend. Abdulkadir et al. (2012) measured the volume fraction of a liquid film of churn and annular flows in an inverted U-bend of R/D = 3 and D = 127 mm by using conductance ring probes. The liquid volume fraction in the straight pipe was larger than that in the bend. They also measured the distributions of the liquid film thickness in the inverted U-bend (Abdulkadir et al., 2014). They reported that the liquid film on the inner side of the bend is thicker than that on the outer side due to the influence of the gravitational force. In Almabrok et al. (2016), Aliyu et al. (2017) and Almabrok et al. (2018), the axial development of the void fraction of upward and downward flows in 5.1m-straight pipes of a serpentine tube of R/D = 2 and D = 101.6 mm was investigated by using a wire mesh sensor. The void fraction at the middle elevation of the pipe was close to that at the bottom of the downflow pipe and that at the top of the upflow pipe, which implies that the influence of the bend on the void fraction disappeared before reaching the middle of the pipe.

The above-mentioned studies dealt with U-bends of $R/D \geq 2$, whereas R/D is close to unity in furnace tube coils. In our previous study, we therefore investigated the flow pattern in the straight pipes of a serpentine tube of R/D = 1.0 and developed a flow pattern map (Kazi et al., 2021). Although the void fractions in the straight pipes were also measured in the previous study, the number of data points was not sufficient, especially for slug flows, to analyze the characteristics of the void fraction in the straight pipes. In addition, we have not yet obtained data of the bend void fractions. In this study, we measured the void fractions of the downward and upward flows in the straight pipes to supplement the void fraction database and assessed the applicability of available correlations to the present data. The void fractions in the bends were also measured and a simple expression of the bend void fractions in terms of the void fractions in the straight pipes was discussed.

2. Experimental

2.1. Experimental setup and condition

Fig. 1 shows the experimental setup. The serpentine tube consisted of the straight pipe for hydraulic entrance section (SE), the top U-bend connected to the entrance section (UTe), the straight pipe for a downward flow (SD), the bottom U-bend (UB), the straight pipe for an upward flow (SU), and the top U-bend (UT) connected to the straight pipe for discharge. The dimensions of the bends were D = 20 mm and R = 20 mm, i.e., the bend diameter ratio, R/D, was 1.0. The bend consisted of two acrylic blocks with a semicircular U-shape to assure the circular cross section and the constant R (Fig. 2). The length of SE was 1700 mm. The lengths, L, of SD and SU were 1500 mm (L/D = 75) and the length of the exit pipe is 500 mm. Air and water were used as the gas and liquid phases, respectively. Air was supplied from the compressor (Anest Iwata, SLP-150EFM6) to the mixing section through the regulator, the pressure gauge and the flowmeter (Nippon Flow Cell, NSP-5 S302, T304). The pump (Iwaki, MD-70R) supplied water from the main tank to the mixing section and the water flow rate was measured using the flowmeter (Nippon Flow Cell, NSP-5 E004). A two-phase flow was formed in SE and flowed through UTe, SD, UB, SU and UT. The experiments were carried out at room temperature (298 $\pm$ 1 K) and atmospheric pressure.

The gas and liquid superficial velocities, J_G and J_L, ranged from 0.5 to 15 m/s and from 0.2 to 1.0 m/s, respectively. Figs. 3(a) and (b) show flow patterns observed at the middle sections of SU and SD, respectively. Slug, churn and annular flows were formed in SU within the present experimental range and the flow pattern transition agrees with the criteria proposed by Mishima and Ishii (1984) except for some churn flow data. The flow patterns formed in SD were slug and annular flows. The present slug flow region is somewhat wider than that predicted by using the transition criteria proposed by Usui (1989).

Flow patterns at large J_G (> 10 m/s) were annular flow in both SU and SD; hereafter this pattern is referred to as the Annular/Annular case. The Slug/Slug case denotes that the flow pattern was slug flow in both SU and SD. Thirteen and three data points were the Slug/Slug and Annular/Annular cases, respectively. In the other cases, the upward slug and churn flows transited to the downward annular flow.

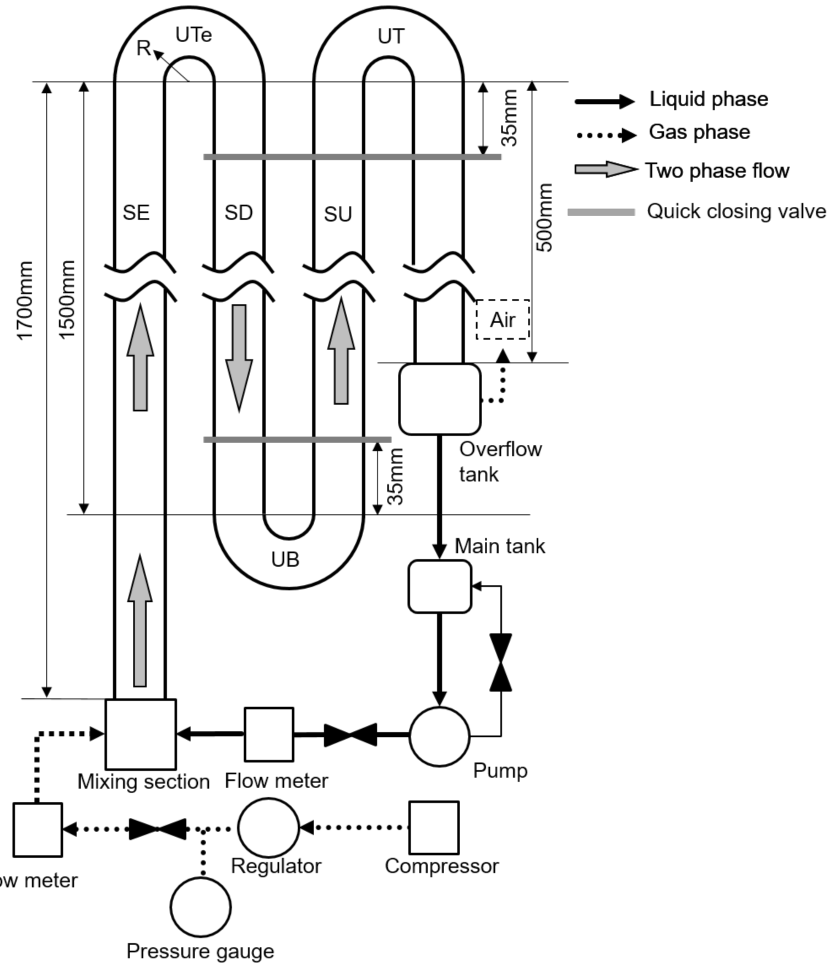


Fig. 1 Experimental setup

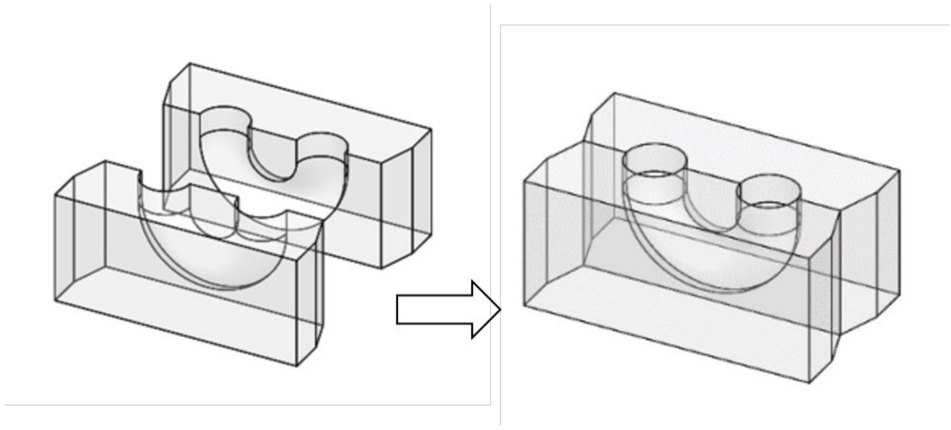
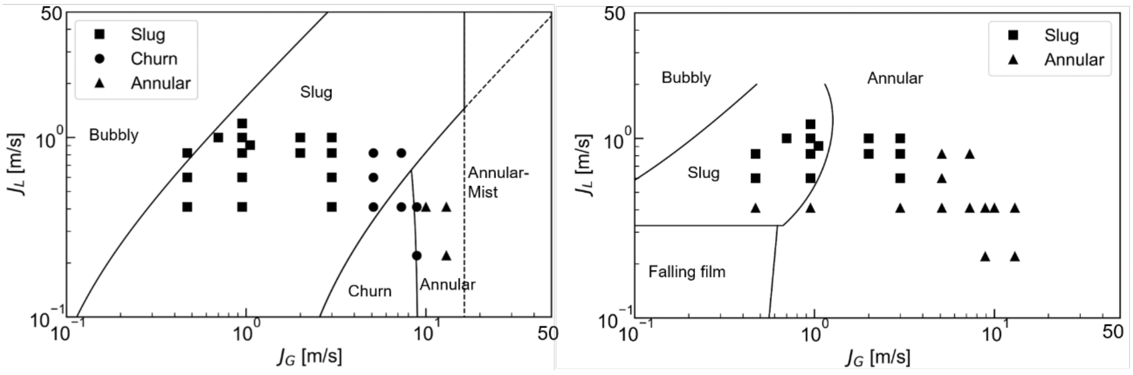


Fig. 2 Composition of U-bend



(a) upward flow (SU) (b) downward flow (SD)

Fig. 3 Flow pattern maps in SU and SD. The transition lines in (a) and (b) are drawn by the criteria proposed by Mishima and Ishii (1984) and Usui (1989), respectively.

2.2. Measurement method of void fraction

The void fractions in SU, SD, UB and UT were measured by using the quick-closing valves (QCVs), which consisted of two pairs of slide plates and air cylinders. The details of the structure are described in our previous studies, e.g. Funahashi et al. (2018). The QCVs were synchronized and closed within 1/30 s. The locations of QCVs were 35 mm above and below the boundaries of UB and UT, respectively, so that the distance, h, between the QCVs was 1430 mm. The void fraction, α_i, of the ith experimental run in SU and SD was obtained by measuring the height, h_i, of accumulated liquid in the measurement section after closing QCVs, i.e.

$$\alpha_i = 1 - \frac{h_i}{h} \tag{1}$$

The amount of the liquid accumulated in the left half of the bend was generally different from that of the right half. We evaluated the liquid volume, $V_{L,Li}$ and $V_{L,Ri}$, in the left and right halves of the bends separately and subtracted them from the volume, V_B, of the bend:

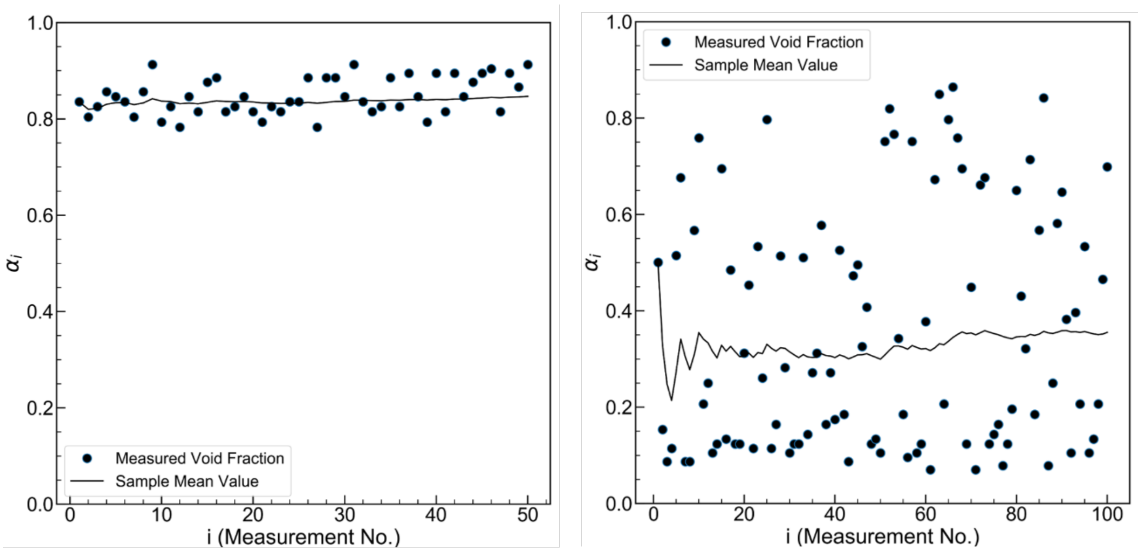
$$\alpha_i = \frac{V_B - V_{L,Li} - V_{L,Ri}}{V_B} \tag{2}$$

We prepared a look-up table for the relation between the height of the liquid in the bend and V_L by using a volume calculation function of the CAD software, SolidWorks, and converted the measured liquid height to V_L. The validity of the conversion curve was confirmed by measuring the liquid height for a prescribed amount of liquid stored into the bend using a syringe.

The mean void fraction, α, was calculated by

$$\alpha = \frac{1}{N}\sum_{i=1}^{N} \alpha_i \tag{3}$$

where N is the number of samples and N was set to 50-100 for convergence of the mean value. The uncertainties in α of SU and SD at 95% confidence were less than 5%. Figs. 4(a) shows α_i and α in the bend with varying N, where J_G = 13.0 m/s and J_L = 0.20 m/s (the Annular/Annular case). The α in the bend converges to a constant value with a small N although α_i show some scatter. Figs. 4(b) shows α_i and α in the Slug/Slug case (J_G = 0.50 m/s and J_L = 0.80 m/s). The scatter of the data is remarkably larger than that in the Annular/Annular case due to the intermittency of the slug flow, so that N required for convergence in α is larger.



(a) UB, Annular / Annular (J_G = 13.0 m/s, J_L = 0.20 m/s)
(b) UT, Slug / Slug (J_G = 0.50 m/s, J_L = 0.80 m/s)

Fig. 4 Convergence of α in Annular/Annular and Slug/Slug conditions

3. Results and discussion

3.1. Flows and void fractions in bends

Fig. 5 shows flows in UB and UT and α in each section at J_L = 0.6 m/s and J_G = 0.95 m/s, which is for the Slug/Slug case. The gas phase flows along the inner side in UB since the liquid phase is moved toward the outer side due to the gravitational and centrifugal forces. The gravitational force also induces stagnation of the liquid in the bend. This liquid stagnation accumulates the liquid within the bend and decreases the cross-sectional area of the gas phase, which results in a breakup of the gas phase. The effect of bending on the flow decreases α. Being similar to the flow in UB, the liquid phase is moved to the outer side and the gas phase flows along the inner side in UT. Bubbles are retarded after flowing through the bend due to the buoyant force and bubble coalescence takes place at the outlet of UT, which causes the formation of a downward slug flow with long bubbles. The α of UB and UT are inbetween α of SU and SD.

Fig. 6 shows flows in UB and UT at J_L = 0.41 m/s and J_G = 13.0 m/s (the Annular/Annular case). Annular flows are formed in all the sections due to the high J_G and smoothly flow through the bends without large fluctuations of the interface. The difference in α between sections is small.

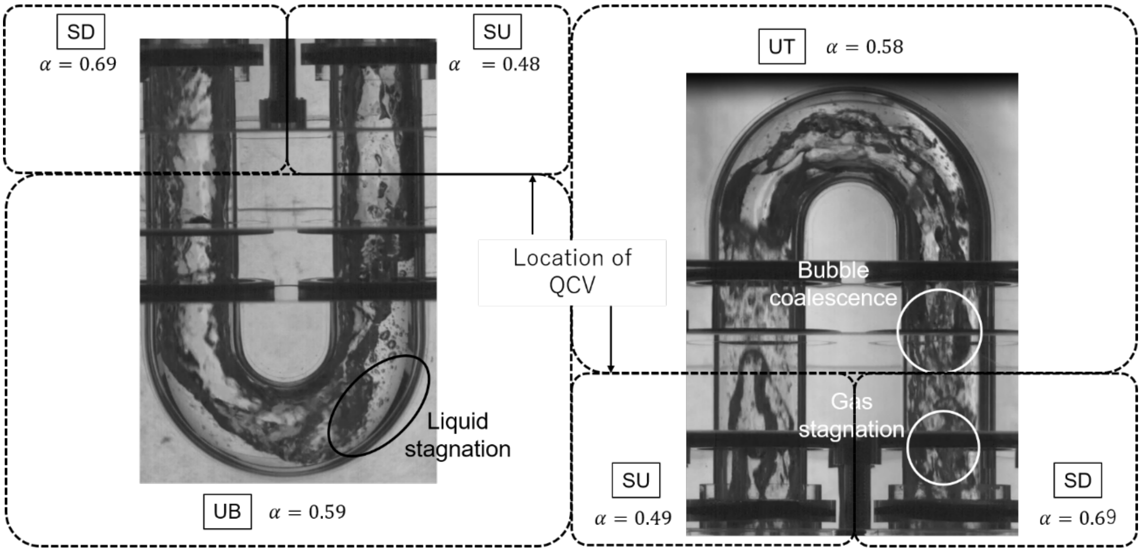


Fig. 5 Flows in UB and UT at J_L = 0.60 m/s and J_G = 0.95 m/s

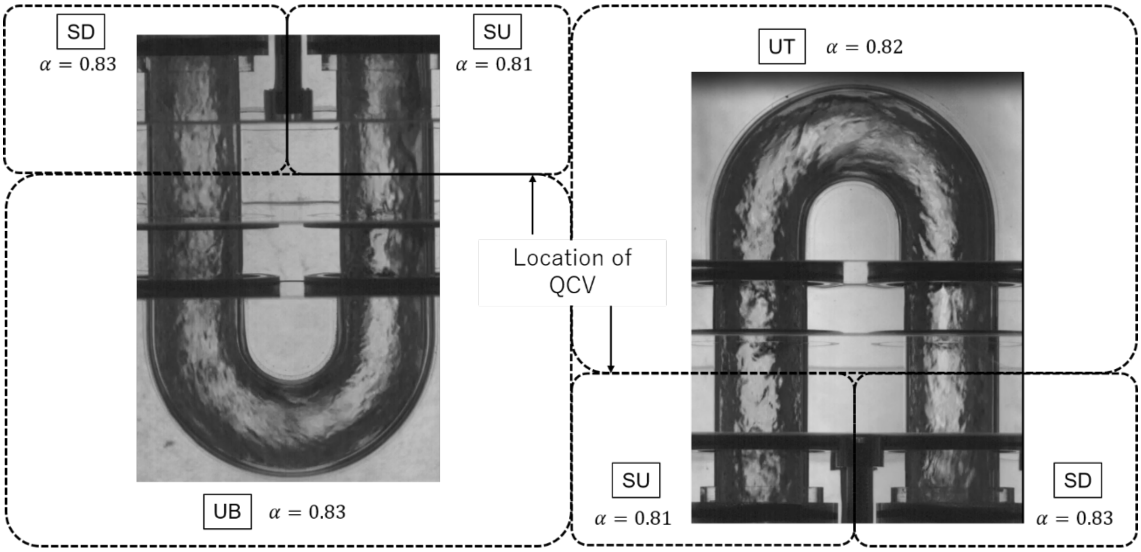


Fig. 6 Flows in UB and UT at $J_L = 0.40$ m/s and $J_G = 13.0$ m/s

Fig. 7 shows α of SU and SD plotted against β (= J_G/J_T), where $J_T = J_G + J_L$. The α of SD are larger than those of SU. The difference between α of SU and SD decreases with increasing β and is small in the Annular/Annular cases. The scatter of α in SD is larger than that in SU, e.g., α = 0.55 in the slug flow of β = 0.54, whereas α = 0.76 in the annular flow even at the same β. On the other hand, the data of SU lie on the single curve even with differences in the flow pattern. Some data of SD are on the homogeneous flow line, α = β, or larger, which implies very large drift velocities due to the opposite direction between the flow and the buoyancy.

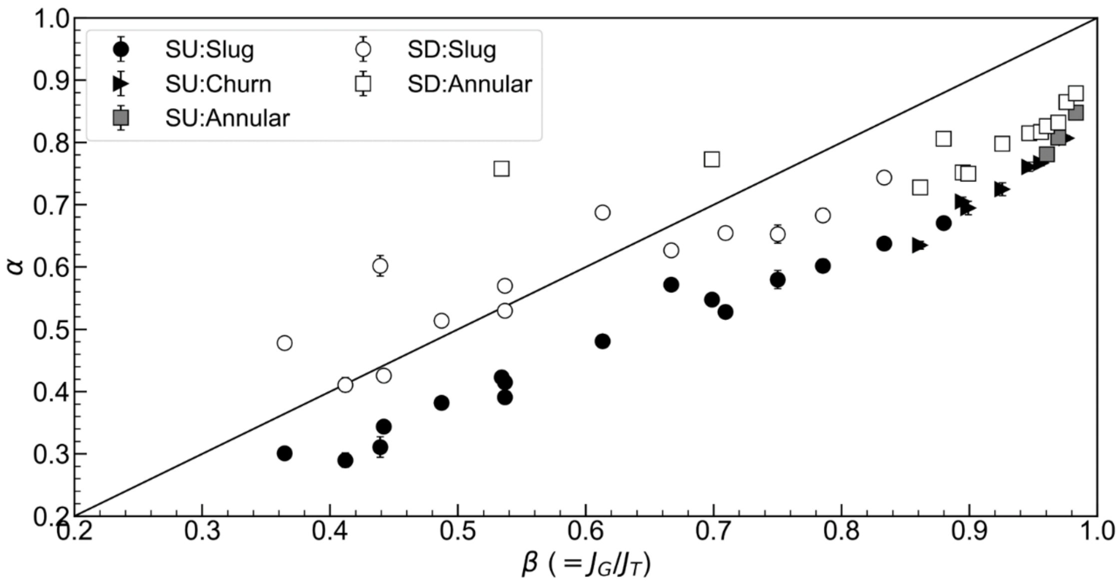


Fig. 7 Measured α of SU and SD plotted against β

3.2. Comparison with correlations for developed flow in straight pipe

The drift-flux plot of the α data of SU is shown in Fig. 8, where the solid line represents the drift-flux model (Zuber and Findlay, 1965) expressed by

$$V_G = C_0 J_T + V_{Gj} \tag{4}$$

or, equivalently,

$$\alpha = \frac{J_G}{C_0 J_T + V_{Gj}} \tag{5}$$

where V_G (= J_G/α) is the gas velocity, C_0 the distribution parameter, and V_{Gj} the drift velocity. The following C_0 and V_{Gj} correlations for developed flows in vertical pipes were used for drawing the lines (Zuber and Findlay, 1965; Ishii, 1977):

$$C_0 = \begin{cases} 1.2 - 0.2\sqrt{\rho_G/\rho_L} & \text{for slug and churn flows} \\ 1 & \text{for annular flow} \end{cases} \tag{6}$$

$$V_{Gj} = \begin{cases} 0.35(\Delta\rho g D/\rho_L)^{1/2} & \text{for slug flow} \\ \sqrt{2}(\Delta\rho g \sigma/\rho_L^2)^{1/4} & \text{for churn flow} \\ 23(\mu_L J_L/\rho_G D)^{1/2}(\Delta\rho/\rho_L) & \text{for annular flow} \end{cases} \tag{7}$$

where ρ is the density, Δρ the density difference between the two phases, g the magnitude of the gravitational acceleration, σ the surface tension, μ the viscosity, and the subscripts G and L denote the gas and liquid phases, respectively. The α data of the slug flow agree with the drift-flux model. The agreement is also reasonable for the churn flow although the model shows some underestimation. Since V_{Gj} for the annular flow includes J_L as the parameter, we drew two lines for J_L = 0.22 and 0.41 m/s. The agreement between the data and the model is fairly good. The churn flow data lie in-between the V_G lines for the churn and annular flows. The data of the slug and annular flows are close to the V_G lines drawn using C_0 and V_{Gj} for the churn flow. In fact, the correlations for the churn flow give reasonable evaluation for the entire experimental range; most data are within ±10% errors as shown in Fig. 9.

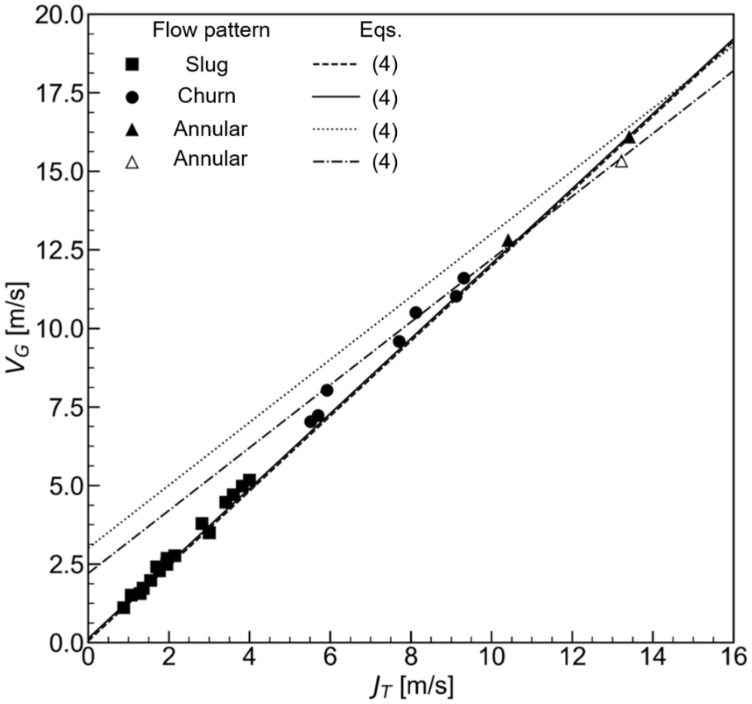


Fig. 8 Relation between V_G and J_T (SU). Eqs. (6) and (7) are used for C_0 and V_{Gj}, respectively, in Eq. (4).

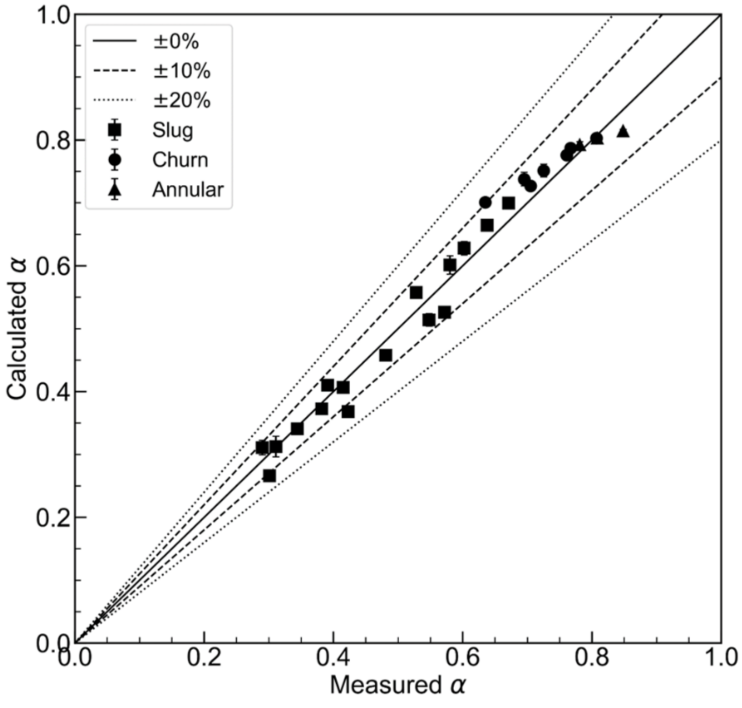


Fig. 9 Comparison between measured void fraction and void correlations for churn flow (SU)

Usui and Sato (1989) proposed the following C_0 and V_{Gj} correlations for developed downward slug flows:

$$C_0 = 1.2 - (2.95 + 350Eo^{-1.3})^{-1} \quad (8)$$
$$V_{Gj} = C_1\sqrt{\Delta\rho g D/\rho_L} \quad (9)$$

where Eo is the Eötvös number defined by

$$Eo = \frac{\Delta\rho g D^2}{\sigma} \quad (10)$$

and the coefficient, C_1, is given by (Wallis, 1969)

$$C_1 = 0.345\left[1 - e^{(3.37-Eo)/10}\right] \quad (11)$$

It should be noted that the superficial velocities in Eq. (5) are negative for downward flows. Usui and Sato (1989) also proposed the following α correlation for downward annular flows:

$$(1-\alpha)^{23/7} - 2Fr_L^2\left[f_W \pm f_i\frac{(1-\alpha)^{16/7}}{\alpha^{5/2}}\frac{\rho_G}{\rho_L}\left(\frac{J_G}{J_L}\right)^2\right] = 0 \quad (12)$$

where Fr_L is the Froude number defined by

$$Fr_L = \frac{J_L}{\sqrt{\Delta\rho g D/\rho_L}} \quad (13)$$

and f_w and f_i are the wall and interfacial friction factors given by $f_w = 0.005$ and $f_i = 0.005[1+75(1-\alpha)]$(Wallis, 1969). In Eq. (12), the plus sign is used when the average gas velocity is smaller than the average liquid velocity, while the negative sign is employed when the former is larger than the latter. Fig. 10 shows the relation between α of SD and J_G/J_L and the correlations for downward flows. The α of the annular flows are well reproduced by Eq. (12) except for the largest J_L case (J_L = 0.82 m/s). On the other hand, the drift-flux model with Eqs. (8) and (9) cannot express the dependence on J_L in the slug flow regime although some data agree with the model. Fig. 11 shows comparisons between the measured and calculated α of SD. The annular flow data are within ±10% errors, while several slug flow data are out of the ±10% errors range.

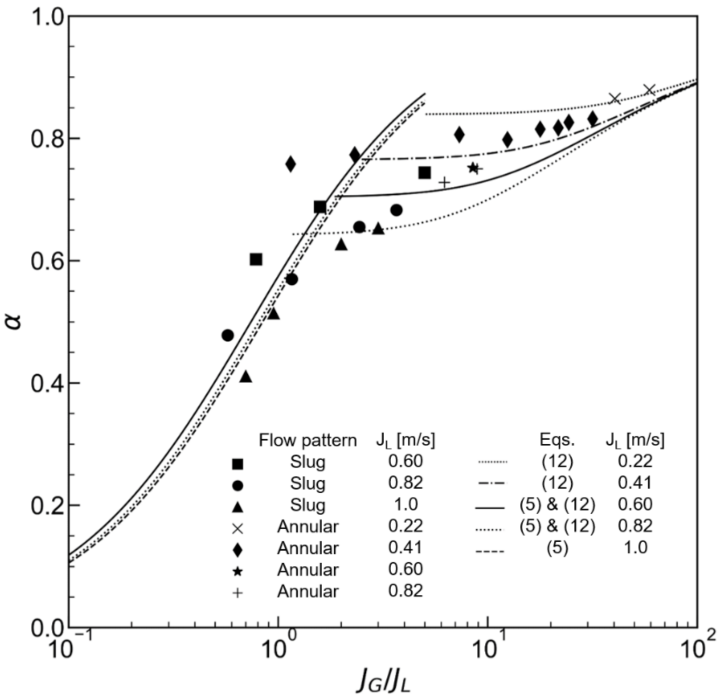


Fig. 10 Relation between α and J_G/J_L (SD). Eqs. (8) and (9) are used for C_0 and V_{Gj}, respectively, in Eq. (5).

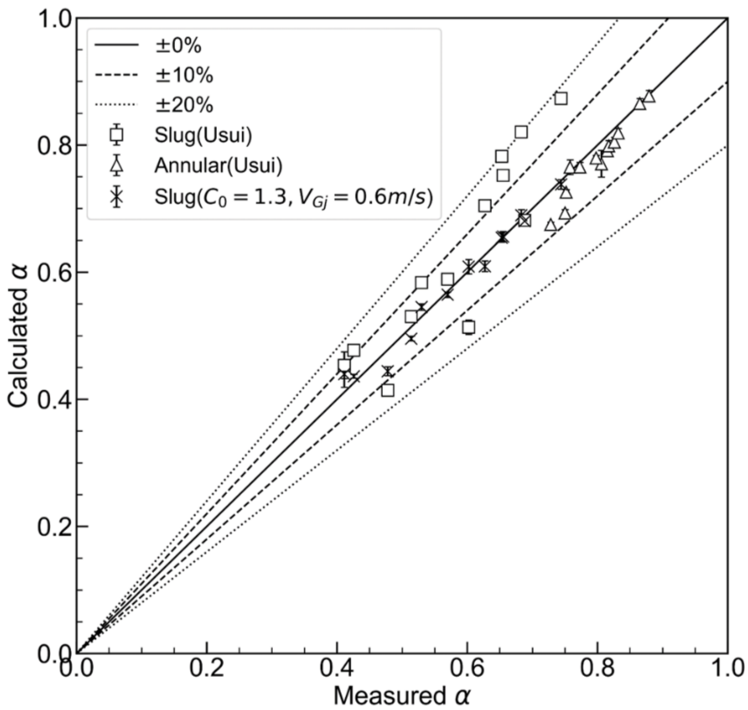


Fig. 11 Comparison between measured void fraction and void fraction correlations (SD)

The α of the downward slug flow are shown in Fig. 12 using the drift-flux plot. The V_G data are linearly dependent on J_T. Fitting the drift-flux model to the present data gives C_0 = 1.3 and V_{Gj} = 0.60 m/s (the broken line), and the model with the fitted values agrees well with the data as shown in Fig. 11 (the cross symbols). The Usui-Sato correlation gives C_0 = 1.0 and V_{Gj} = 0.15 m/s. The C_0 of the Usui correlation is smaller than the fitted value. The slug flow data used in Usui and Sato (1989) for developing the C_0 correlation included isolated large bubbles, whose interfaces were smooth. On the other hand, Goda et al. (2003) pointed out that the flow structure of a downward slug flow is chaotic like an upward churn-turbulent flow, and they obtained experimentally $C_0 \sim 1.2$ and, in some conditions $C_0 \sim 1.3$. Large bubbles in the present slug flows were highly unstable even at low J_T conditions, and therefore, the value of C_0 was close to that of Goda et al. (2003) and Ishii (C_0 = 1.2).

The V_{Gj} in the present data is four times larger than Eq. (9). Since α of SU is much smaller than that of SD, the mixture density in SU is larger than that in SD. The difference in the substantial elevation head between SD and SU thus acts on the fluid passing through UB as a flow residence, which may cause a significant retardation of the downward motion of bubbles in SD. The retardation effect is obviously shown in Fig. 13; the large bubble cannot smoothly enter into UB and the position of the bubble nose does not change even after several tens of micro-seconds. The large V_{Gj} is therefore a direct consequence of the retardation effect, and this phenomenon is a distinguishing feature of the serpentine tube arrangement.

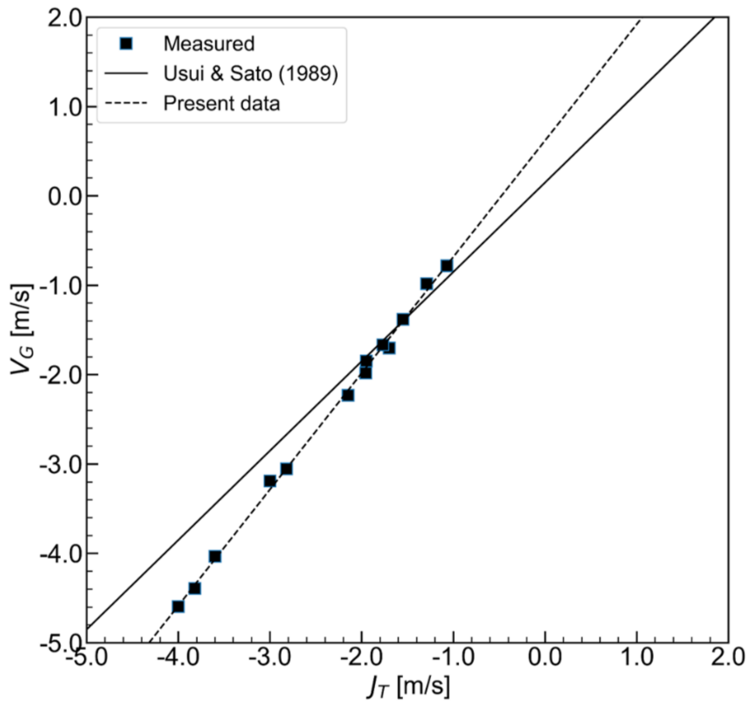


Fig. 12 Drift-flux plot for downward slug flow

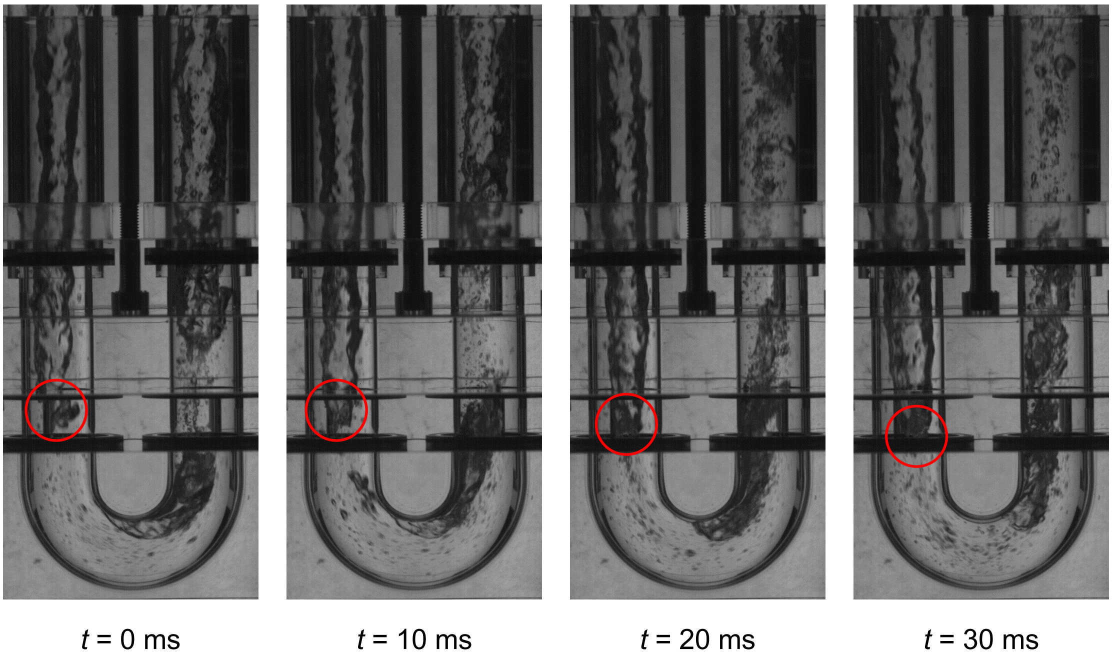


Fig.13 Bubble retardation effect (J_L =1.0 m/s, J_G =1.0 m/s)

3.3. Void fractions in UT and UB

Fig. 14 shows α of UT and UB. The α of SU and SD are also plotted. The α of UT and UB are inbetween α of SU and SD. As discussed in Sec. 3.1, the void fractions in each section are almost the same in the Annular/Annular case. The α of UT and UB in the Slug/Slug cases lie between those of UT and UB. This result implies that the bends smoothly change the flow structure between those of the downward and upward flows. It is thus expected that α in both UB and UT can be estimated by simply averaging those of SU and SD:

$$\alpha = \frac{1}{2}(\alpha_{SU} + \alpha_{SD}) \tag{14}$$

where α_{SU} and α_{SD} are the void fractions of SU and SD, respectively. Figs. 15(a) and (b) show comparisons between Eq. (14) and α of UT and UB, respectively, where measured α_{SU} and α_{SD} are used for Eq. (14). Most bend void fractions calculated using Eq. (14) lie to within ±10% errors. The mean with the same weight for α_{SU} and α_{SD} works well. This fact implies that the transition of the flow structure from SU (SD) to SD (SU) was almost completed at the bend exits since α at the bend inlets would be almost the same as those of the upstream straight pipes.

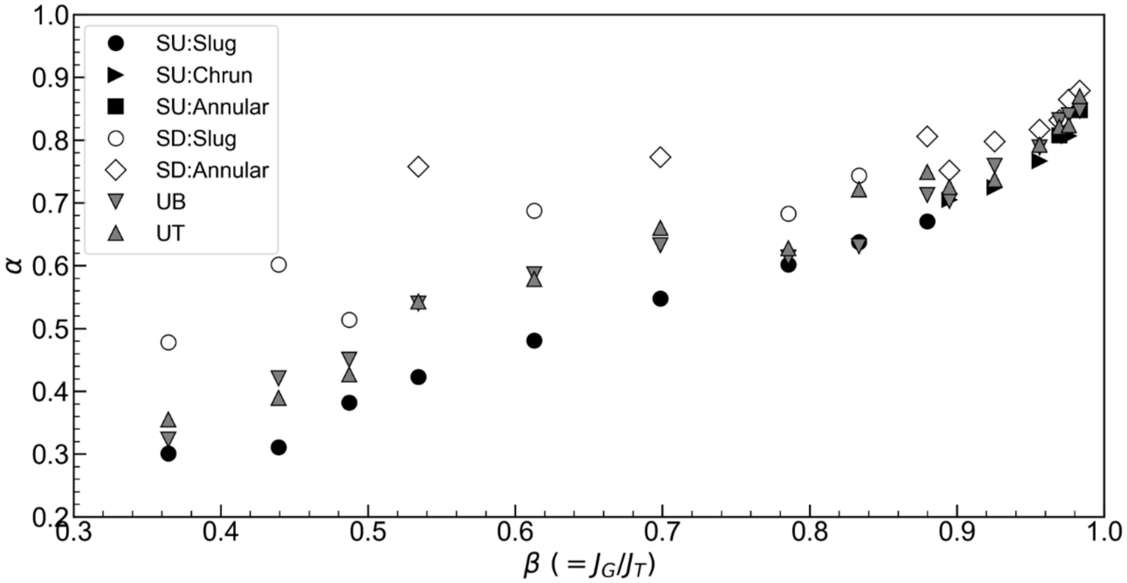


Fig. 14 Measured void fractions of UT and UB

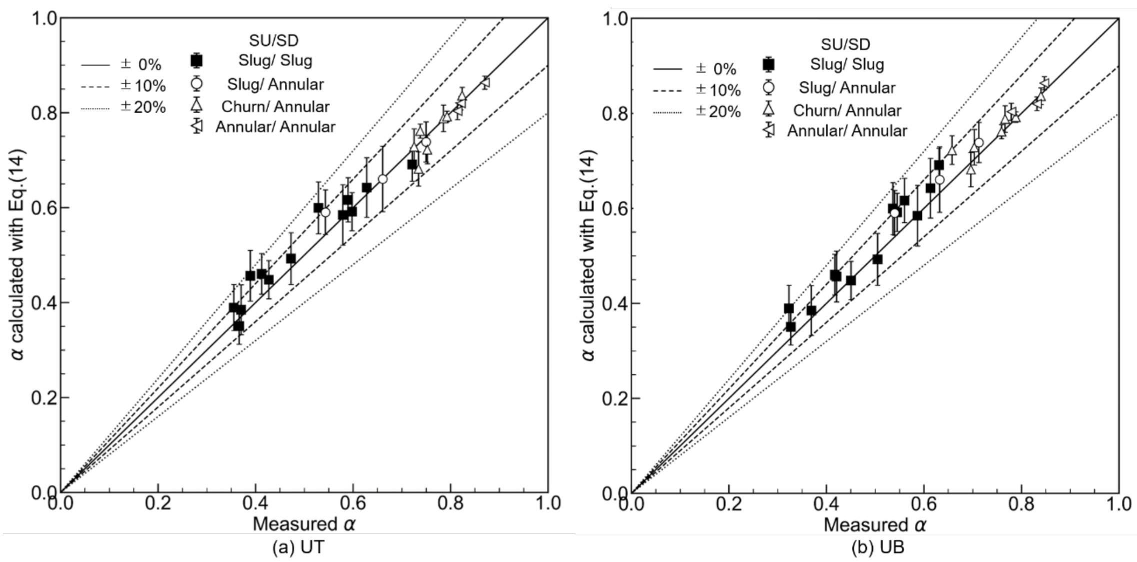


Fig.15 Comparisons between α of (a) UT and (b) UB and Eq. (14)

Figs. 16(a) and (b) show comparisons between α of UT and UB and those evaluated using Eq. (14) with the void fraction correlations for the straight pipes; Eqs. (5)-(7) for α_{SU}, Eq. (5) with C_0 and V_{Gj} fitted to the data for α_{SD} of the slug flow, and Eq. (12) for α_{SD} of the annular flow. Most data are within ±10% errors, and therefore, the bend void fractions can be estimated using void correlations for the straight pipes, i.e. the void correlations for co-current flows in vertical pipes. It should however be noted that the serpentine tube strongly affects the drift velocity of the downward slug flow as discussed above and using α correlations for vertical pipes would give errors in the bend void fractions.

Modeling V_{Gj} for the downward slug flow in serpentine tube arrangements remains as a future work.

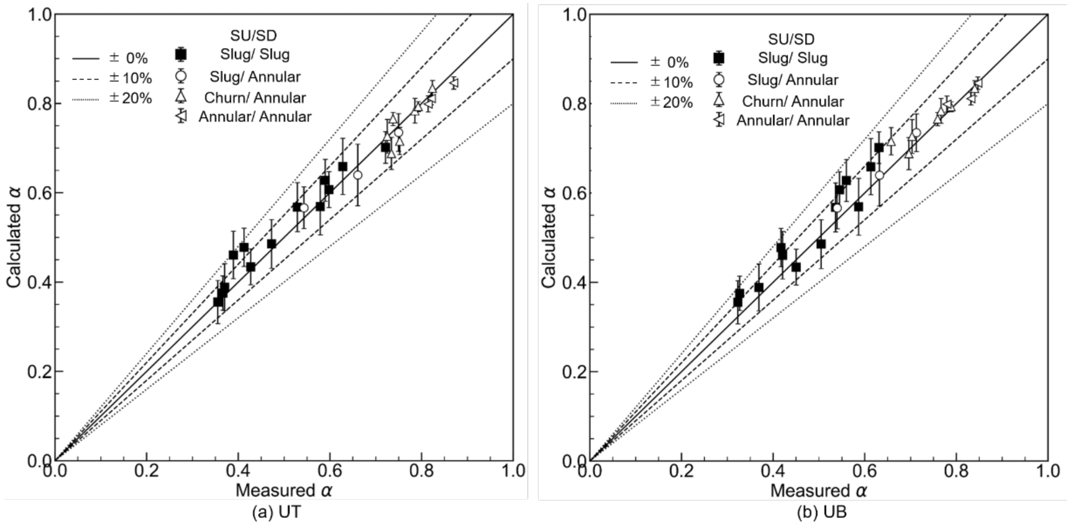


Fig. 16 Comparison between α of UT and UB and α evaluated with correlations

4. Conclusions

Experiments on air-water two-phase flows in a serpentine tube of $R/D = 1$ were carried out to understand the characteristics of the void fractions in each section, i.e. the downward-flow section (SD), the upward-flow section (SU), the top U-bend (UT), and the bottom U-bend (UB). The void fractions were measured by using the quick-closing valve method. The flow patterns in the downward flow were slug and annular flows, and those in the upward flows were slug, churn and annular flows. The applicability of available void correlations for vertical pipes to the present data and an evaluation method for the bend void fraction were discussed. The following conclusions were obtained:

(1) The drift-flux model with available correlations of the distribution parameter, C_0, and drift velocity, V_{Gj}, for developed co-current flows agrees with the void fractions of SU, and Usui's correlation expressed in terms of the Froude number gives good agreement with the void fractions of downward annular flows.

(2) The serpentine tube arrangement largely increases the drift velocity of the downward slug flow due to a large difference between the void fractions in SD and SU.

(3) The void fractions in UT and UB are well estimated by averaging those of SU and SD, which implies that the transition of the flow structure between the straight sections is almost completed within the bends.

(4) The bend void fractions are well evaluated by averaging the void fractions calculated by the correlations for SU and SD.

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