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Technical Note

Two-phase slug flow across small diameter tubes with the presence of vertical return bend

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Abstract

This study examines the two-phase slug flow across small diameter tubes with the presence of vertical U-type return bends. The translational velocity of the air slug across return bend usually peaks at an angle of $\pi/2$–$3\pi/4$. The increase of translational velocity is especially pronounced when flow enters at the lower tube with a smaller curvature ratio. An approximately twofold increase of the slug velocity is observed at a curvature ratio of 3. Dimensionless correlations for flowing upwards and downwards with a mean deviation of 18.7% and 24.5% are proposed that can describe the variation of translational velocity within the return bend.

Keywords: Slug flow; Return bend; Translational velocity

1. Introduction

Two-phase gas-liquid flow in a pipeline takes a variety form of configurations in association with the distribution of two phases. One of the most complicated flow patterns with unsteadiness is the intermittent or slug flow. Because of its unsteady nature, the prediction of the corresponding pressure drop, heat, and mass transfer is a difficult task.

For investigations of the slug flow in vertical, horizontal, and inclined tubes, many researches were available in the literature [1–3]. Notice that the existing studies concerning with the slug flow pattern are only for straight tubes. However, in real thermofluids system, exploitation of the curved tubes for connection is very common. The curved tubes may be either functioned as a connection tube to save space (e.g. hairpin) or operated as a heat transfer surfaces (e.g. U-tube bundle in shell-and-tube application and refrigerator heat exchangers). For single-phase flow, it is well known that a secondary flow is generated when fluid flows across the curve channel [4]. Thus, the fluid flow characteristics are rather complicated since the centrifugal force drives the more rapid fluid in the concave part of the curve channel while the fluid in the convex parts is slowing down. The magnitude of such secondary flows is reduced with an increase of bend radius (R), and with a decrease of fluid velocity. For two-phase flow, things get even more complex because of the unequal density, phase velocity, and relevant properties. There are many studies related to

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Nomenclature

A	$A = \frac{\frac{gD^2(\rho_f-\rho_g)}{\sigma}\left(\frac{x}{1-x}\right)}{\left(\frac{2R}{D}\right)\left(\frac{J\mu_f}{\sigma}*10\right)}$ (shown in ordinate of Fig. 3)
D	inside diameter of the tube (m)
G	total mass flux (kg/m^2 s)
g	gravity of acceleration (m/s^2)
J	superficial velocity (m/s)
R	curvature radius of the return bend (m)
t	time (s)
V_b	translational velocity of air slug (m/s)
x	vapor quality
X	position started for slug flow entering the return bend (m)
σ	surface tension (N/m)
μ_f	liquid viscosity (Pa s)
ρ_f	liquid density (kg/m^3)
ρ_g	gas density (kg/m^3)

the heat transfer and frictional characteristics in helical coils but only some reports were relevant to the two-phase thermalfluids characteristics in U-type return bends. In contrast to the flow pattern in helical coils that reached a quasi-equilibrium condition, the flow pattern in return bend was observed to readjust itself very rapidly by secondary motions, especially for stratified and semiannual flows. The flow regime transition from stratified to annular flow was shown to appear over a fairly wide range [5].

There were some investigations focused on the heat transfer, and frictional performance with the presence of U-tube configurations [6,7]. For detailing the flow patterns across return bend, only the works by Wang et al. [7] and Chen et al. [8] are relevant to this subject. Both studies conducted a two-phase flow pattern visualization for the air–water mixtures through nine horizontal return bends ($D = 3, 5, 6.9$ mm) having curvature ratios of 3–7.1. They had provided some qualitative description about the two-phase flow across the horizontal return bends. One of the interesting features is the momentary change from stratified flow to annular flow after the return bend. However, their studies were pertinent to horizontal arrangement only and no detailed quantitative description of the slug flow pattern was reported. In this regard, it is the purpose of this study to examine the relevant characteristics of the slug flow such as change of flow pattern and the translational velocities across the vertical return bend.

2. Test facility

The test rig is designed to conduct tests with air–water mixtures. Detailed description of the test facility and the measurement instrumentations can be found in Chen et al. [8]. The inlet temperatures of the two-phase mixture are near 25 °C. Four glass tubes having different curvature ratios are used for testing. Two 3.0 mm diameter tube have the curvature ratio ($2R/D$) of 3.0 and 7.0, and two 6.9 mm diameter tubes have the curvature ratios of 3.04 and 7.0, respectively. Observations of flow patterns are obtained from images produced by a high speed camera of Redlake Motionscope PCI 8000s.

3. Results and discussion

Photographs that are representative of the observed slug flow entering at the lower tube for $D = 6.9$ mm with curvature ratios of 3 and 7 at a mass flow flux of 50 kg/m^2 s having vapor qualities of 0.001 are displayed in Fig. 1 for showing the flow progression in the presence of return bend. As the slug is approaching the return bend (Fig. 1(a) and (b)), the air slug then make a turn to climb up the return bend by both centrifugal force and buoyancy force. Due to the significant density difference and the influence of gravity, the speed of the air slug is comparatively higher than that of the liquid that is initially in front of the slug. Hence the air slug is forced to penetrate the liquid in front of it. Additionally, because of the presence of the centrifugal force, the liquid was forced to the concave part of the return bend. The resultant interactions of the air slug and the liquid portion at the concave part make a small portion of the liquid at the concave portion unable to climb the return bend and is further pushed backwards to become a reversed flow (Fig. 1(c)). This special phenomenon is associated with the gravity force and the reaction force of the air slug. The amplitude of reversed liquid then hits the gas flow in the same slug to separate the original elongated slug into two smaller slugs (Fig. 1(d)). For the same vapor quality and mass flux, with an increase of curvature ratio to 7, the flow reversal phenomenon is not seen (Fig. 1(g)–(j)) because the centrifugal force is comparatively small. In addition, the air slug is neither separated at the return bend nor remerged after the return bend because of the lack of flow reversal phenomenon.

As the elongated slug entering at the upper tube for $x = 0.001$ and $D = 6.9$ mm, the air slug is forced to flow

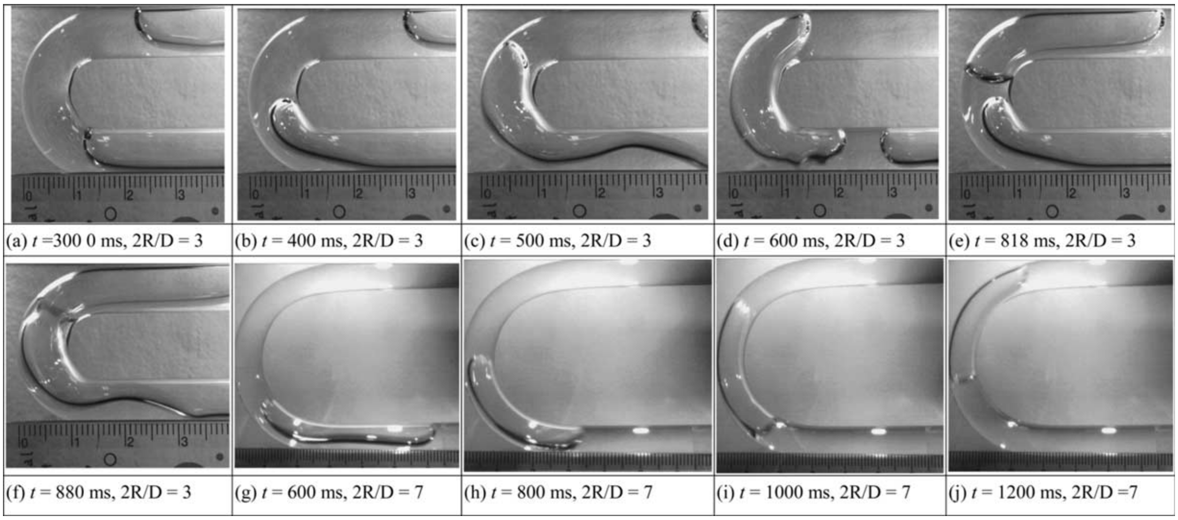

Fig. 1. Progress of slug flow entering at the lower tube (flowing upwards) at $D = 6.9$ mm, $G = 50$ kg/m^2 s and $x = 0.001$.

downwards with the resistance of the buoyancy force. The portion of slug nose continues to moves further downstream while its main body is still trapped in the return bend (slug "freezing") due to buoyancy force. This eventually leads to a separation of the air slug. When compared to the flow pattern having a horizontal configuration [5,8], this "freezing slug" phenomenon is only seen in the present vertical arrangements with flow entering at the upper tube.

With a further increase of mass flux and flow quality, one can see these phenomena of freezing and flow reversal gradually disappear. This is expected since the influence of flow inertia takes over. For smaller tube diameter ($D = 3$ mm), the above discussed flow reversal and freezing phenomena are hardly seen due to the influence of the flow inertia and surface tension.

For detailing the flow patterns across return bend, Wang et al. [5] had identified the two-phase flow across the return bend into five regions: (I) upstream region; (II) deaccelerating region; (III) return bend; (IV) recovery region; and (V) downstream region. Apparently, the translational velocity of the air slug across the return bend is increased from the inlet of the U bend due to the centrifugal force. Since the flow resistance and heat transfer are strongly related to the slug velocity in the return bend, the slug velocity along the 180° bend is measured and given in Fig. 2 which shows the change of slug velocity along the return bend of $D = 3$ and 6.9 mm. Usually, counting from the inlet, the highest translational velocity peaks at an angle near $\pi/2$–$3\pi/4$. This is due to the imposed centrifugal force managed to increase the translational velocity inside the return bend. As is seen in the figure, an approximately two-fold increase of the translational velocity is seen near $\pi/2$–$3\pi/4$ for the slug entering at the lower tube and heading upwards with $2R/D = 7$. In addition to the imposed centrifugal force, the significant increase of the translational velocity is reinforced with the presence of buoyancy force. By contrast, for the air slug entering the return bend at the upper tube, although the centrifugal force still manages to increase the slug velocity, the buoyancy force acts to resist the slug velocity, thereby reducing the slug velocity considerably. In some circumstance, such as those aforementioned "freezing slug", the slug velocity may be even smaller than that at the entrance. For the flow entering at the lower tube, variation of slug velocity is more pronounced at a larger curvature ratio. This result implies centrifugal force is the dominant force at a smaller curvature ratio. Based on the present flow visualizations and measurements, the translational velocity of the air slug is related to the buoyancy force, centrifugal force, curvature ratio, and mass flow inertia. As a consequence, efforts were made to correlate the translational velocity of air slug based on the dimensionless parameters like $J/V_b, \frac{gD^2(\rho_f-\rho_g)}{\sigma}, \left(\frac{x}{1-x}\right)$, X/D, and $2R/D$ [9]. Notice that the first group represents the ratio between the total superficial velocity and the slug velocity; the second group denotes the relative importance of buoyancy and surface-tension forces; and the third group characterizes the relative influence of gas phase to liquid phase. Two correlations for the translational air slug velocity flowing upwards and downwards are given. However, the developed correlations exclude the portion having freezing slug due to its extremely complex nature. The developed correlations for flowing upwards and downwards are given in Eqs. (1) and (2), respectively.

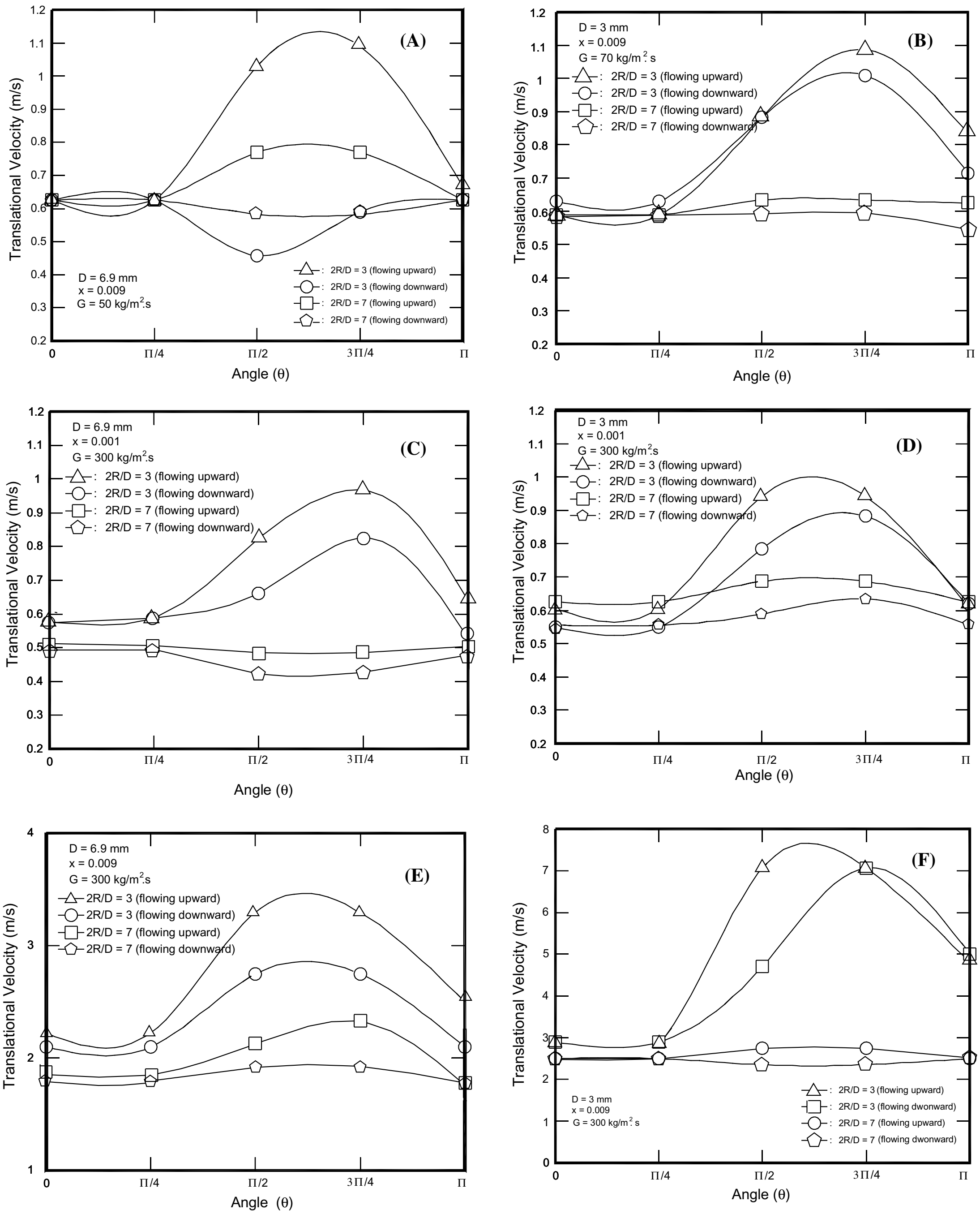

Fig. 2. Translational velocities of the air slug across the vertical return bend.

$$\frac{J}{V_b} = \ln\left[3.55 + 0.57\left(\frac{X}{D}\right)^{1.177} - \left(\frac{X}{D}\right)\right] - 0.1\left[\frac{\frac{gD^2(\rho_f-\rho_g)}{\sigma}\left(\frac{x}{1-x}\right)}{\left(\frac{2R}{D}\right)\left(\frac{J\mu_f}{\sigma}\right)}\right] \text{ flowing upwards} \quad (1)$$

$$\frac{J}{V_b} = \frac{14}{\exp\left[2.012 + 1.45\left(\frac{X}{D}\right)^{0.877} - \left(\frac{X}{D}\right)\right]} - 0.1\left[\frac{\frac{gD^2(\rho_f-\rho_g)}{\sigma}\left(\frac{x}{1-x}\right)}{\left(\frac{2R}{D}\right)\left(\frac{J\mu_f}{\sigma}\right)}\right] \text{ flowing downwards} \quad (2)$$

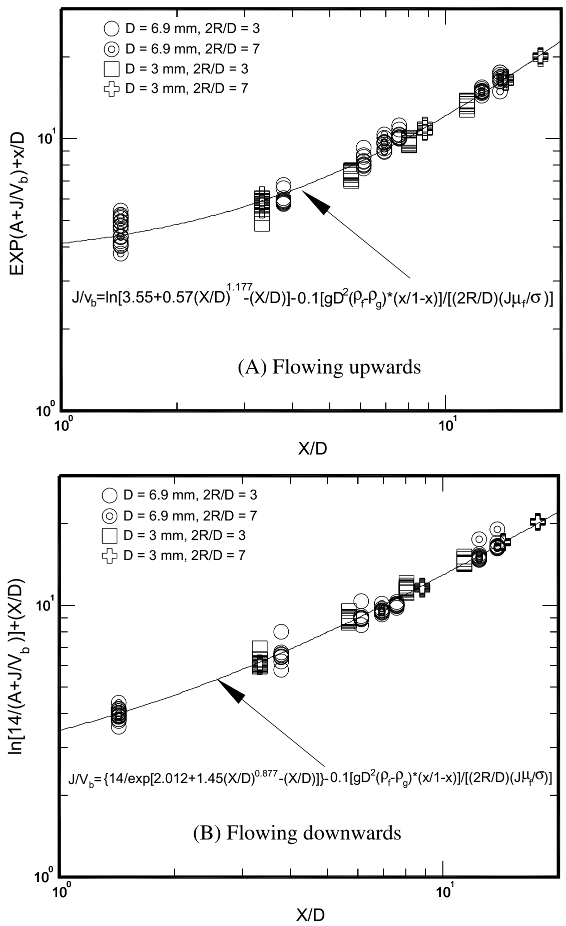

Fig. 3. Comparison of translational velocities of the air slug across the vertical return bend.

Comparisons of the proposed correlations with the experimental data are shown in Fig. 3 with a mean deviation of 18.7% and 24.5% for Eqs. (1) and (2), respectively.

4. Concluding remarks

For slug flow entering at the lower tube with a total mass flux of 50 kg/m^2 s and $D = 6.9$ mm having a small curvature ratio of 3, a flow reversal phenomenon is observed at the entrance region of the return bend. The flow reversal phenomenon is not seen if the flow entering at the top of the tube, instead, a very special "freezing slug" phenomenon is observed. However, for $D = 3$ mm, the flow reversal and freezing slug phenomena are not seen.

The translational velocity of the air slug across return bend usually peaks at an angle of $\pi/2$–$3\pi/4$. Generally the increase of translational velocity is especially pronounced for flow entering at the lower tube and at a smaller curvature ratio. An approximately twofold increase of the slug velocity is observed at a curvature ratio of 3. Dimensionless correlations are proposed that can describe the translational velocity for flowing upwards and downwards within the return bend with a mean deviation of 18.7% and 24.5%, respectively.

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References

[1] M. Kawaji, J.M. DeJesus, G. Tudose, Investigation of flow structures in vertical slug flow, Nucl. Eng. Des. 175 (1997) 37–48.
[2] G.H. Abdul-Majeed, Liquid slug holdup in horizontal and slightly inclined two-phase slug flow, J. Pet. Sci. Eng. 27 (2000) 27–32.
[3] R. van Hout, D. Barnea, L. Shemer, Translational velocities of elongated bubbles in continuous slug flow, Int. J. Multiphase Flow 28 (8) (2002) 1333–1350.
[4] W.R. Dean, Note on the motion of fluid in curved pipe, Philos. Mag. 4 (1927) 208–223.
[5] C.C. Wang, I.Y. Chen, Y.W. Yang, Y.J. Chang, Two-phase flow pattern in small diameter tubes with the presence of return bend, Int. J. Heat Mass Transfer 46 (2003) 2975–2981.
[6] K. Cho, S.J. Tae, Condensation heat transfer for R-22 and R-407 refrigerant–oil mixtures in a microfin tube with a U-bend, Int. J. Heat Mass Transfer 44 (2001) 2043–2051.
[7] C.C. Wang, I.Y. Chen, H.J. Shyu, Frictional performance of R-22 and R-410A inside a 5.0 mm wavy diameter tube, Int. J. Heat and Mass Transfer 46 (2003) 755–760.
[8] I.Y. Chen, Y.W. Yang, C.C. Wang, Influence of horizontal return bend on the two-phase flow pattern in a 6.9-mm diameter tube, Can. J. Chem. Eng. 80 (3) (2002) 478–484.
[9] G.B. Wallis, One-dimensional Two-phase Flow, McGraw-Hill Inc., 1969, pp. 299–304.