# TWO-PHASE FLOW PATTERNS IN A 90° BEND AT MICROGRAVITY\*

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**ABSTRACT**: Bends are widely used in pipelines carrying single- and two-phase fluids in both ground and space applications. In particular, they play more important role in space applications due to the extreme spatial constraints. In the present study, a set of experimental data of two-phase flow patterns and their transitions in a 90° bend with inner diameter of 12.7 mm and curvature radius of 76.5 mm at microgravity conditions are reported. Gas and liquid superficial velocities are found to range from  $(1.0 \sim 23.6)$  m/s for gas and  $(0.09 \sim 0.5)$  m/s for liquid, respectively. Three major flow patterns, namely slug, slug-annular transitional, and annular flows, are observed in this study. Focusing on the differences between flow patterns in bends and their counterparts in straight pipes, detailed analyses of their characteristics are made. The transitions between adjoining flow patterns are found to be more or less the same as those in straight pipes, and can be predicted using Weber number models satisfactorily. The reasons for such agreement are carefully examined.

KEY WORDS: two-phase flow, flow patterns, 90° bend, microgravity

#### **1 INTRODUCTION**

Bends as well as other fittings are widely used in pipelines carrying single- and two-phase fluids in both ground and space applications. In the latter case, they are used more frequently due to the extreme spatial constraints, and the "minor" pressure drops in the fittings may thus outweigh the "major" pressure drops in straight pipes. It is thus important for the design engineer to have reliable design procedures to estimate the magnitude of pressure drops in the fittings strongly depends on the flow structure of the two-phase flow in the fittings; particularly, the phase separation, local vortex generation and wall detachment.

Previous investigations on two-phase flows at microgravity conditions focused upon the flow patterns and their transitions, the pressure drops, and the heat transfer coefficients in straight pipes under a fully developed state, which implies that the straight test sections must have a much large lengthto-diameter ratio. On the progress in this field, several comprehensive reviews are available. They are authored by Rezkallah<sup>[1]</sup>, Colin et al.<sup>[2]</sup>, Hewitt<sup>[3]</sup>, Zhao<sup>[4]</sup>, and Gabriel<sup>[5]</sup>, among many others.

Unlike the case of straight pipes, fewer experiments were performed at microgravity conditions to study two-phase flows in pipe fittings, including contractions<sup>[6]</sup>, T-junctions<sup>[7]</sup>, and coiled pipes<sup>[8]</sup>. Most recently, Berg et al.<sup>[9]</sup> performed a series of experiments on two-phase flows in a 90° bend at microgravity conditions in the drop tower ZARM, which can provide a duration lasting 4.74 s with a residual gravitational acceleration of no more than  $10^{-4}$  m/s<sup>2</sup>. The observed flow patterns were classified as bubble and slug flows in their study. No shift of the transitional boundary was observed. The pressure drops in the bend and in the straight pipe were also measured. However, the measurement method was different from

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that widely used in the literature for measuring the pressure drops in bends, which may lead to some problems in interpreting their data.

Generally, two-phase flows in the fittings are transient, non-equilibrium, and thus much more complicated when compared to those in straight pipes. In the present work, we focus on the case of  $90^{\circ}$  bends. The gradual change of the flow direction causes a centrifugal force directed from the centre of curvature to the outer wall. As a result, a secondary flow occurs in the bend. Such a flow is well known in single-phase flows. The secondary flow, along with the local vortex generation and wall detachment, causes an excess pressure loss when compared to that in a straight pipe with the same mean length and diameter. However, the presence of the second phase and their distribution introduce further complications. Patterns of the secondary flow of two-phase flows in bends may be widely different from those of single-phase flows. Furthermore, separation of the phases may occur due to the effects of the centrifugal force which tends to move the liquid towards the outside of the bend. Separation in this way is likely to give rise to a significant slip or relative motion effects between the phases. The resultant flow structure may become much more complicated than that in straight pipes, and greatly influence other flow parameters such as the pressure drops in the bend.

In most of the up-to-date models/correlations about two-phase flows in bends, the effect of the phase separation is usually taken into account, but the difference of the pattern of secondary flows between single- and two-phase flows is rarely studied. In the present study, the characteristics of flow patterns and their transitions of two-phase flows in a  $90^{\circ}$ bend at microgravity conditions are reported and analyzed. Much attention is paid to the difference of the flow structure between single- and two-phase flows. This information may be valuable for more sophisticated modeling of two-phase flows in bends in the future.

## 2 EXPERIMENTAL FACILITY

A two-phase, two-component experimental facility was designed and built in 1990 at the University of Saskatchewan to conduct experiments in two-phase flows in straight pipes and 90° bends at microgravity aboard NASA's KC-135 aircraft. A detailed description of the experimental facility and the flow pattern results in straight pipes can be found in Zhao & Rezkallah<sup>[10]</sup>. Only those concerned with two-phase flows in the bend are discussed in detail here (Fig.1).



Fig.1 Schematic of the experimental facility

Water and air were used as the working fluids. Distilled, de-ionized water was pumped in a closed loop from a pump/separator unit to the experimental test sections and back to the pump/separator. Water flow rate was varied by adjusting the rotational speed of the pump and a set of flow control venturis. It was measured using two turbine flow meters with an accuracy of 1% in full scale. Air was supplied from a compressed air tank attached to the facility. The air flow rate was controlled and measured using a mass flow controller. The controller had a range of  $(0 \sim 100)$  SLM (standard liters per minute), and an accuracy of 1% in full scale. All turbine flow meters and mass flow controller were calibrated prior to and after each flight.

The two-phase flow was supplied through a mixer, followed by a vertical straight test section. The vertical straight test section is 9.525 mm ID, and has a total length of 1.5 m. It consists of three parts: a calming section (L = 80 cm), a vertical observation section  $(L = 12.7 \,\mathrm{cm})$ , and a heated section (L = 36 cm). The absolute pressure at the outlet of the calming section was measured using a Validyne<sup>©</sup> pressure transducer with a range of  $(0 \sim 340)$  kPa  $((0 \sim 50) \text{ psi})$ . The differential pressure between this point and the outlet of the heated section was also measured by a Validyne<sup>©</sup> pressure transducer with a range of  $(0 \sim 13.8)$  kPa  $((0 \sim 2)$  psi). The accuracy of the pressure transducers is 0.5% in full scale. The fluid temperature at the outlet of the heated section is measured using Platinum RTD (Resistance Temperature Devices) with an accuracy of 0.1°C. All of the transducers were carefully calibrated before the flight campaign.

Immediately after the heated section, the twophase flow direction was inverted 180° through a U bend with an inner diameter of 12.7 mm and a curvature radius of approximately 35 mm. The flow was then directed downwards in a clear pipe of 12.7 mm ID and 58.4 cm long. At the end of the down-comer, the flow direction was changed to horizontal through a  $90^{\circ}$ bend, which had an inner diameter of 12.7 mm and a curvature radius of 76.5 mm. The horizontal observation section is 12.7 mm ID and 39.4 cm long. All three observation sections, including the vertical straight section, the  $90^{\circ}$  bend, and the horizontal straight section, are immersed in a light path corrector to reduce image distortion near the wall due to the curvature of the pipe. Three cameras were used to record the flow patterns in three observation sections. The flow pattern in the  $90^{\circ}$  bend, for example, was recorded on a SONY Hi-8 video camera with shutter speed of  $1/1000 \, s.$ 

## **3 RESULTS AND DISCUSSIONS**

The ranges of the gas and liquid superficial velocities studied in the present work are  $U_{\rm SG} = (1.0 \sim 23.6) \,\mathrm{m/s}$  and  $U_{\rm SL} = (0.09 \sim 0.5) \,\mathrm{m/s}$ , respectively. The system pressure varied from 53 kPa to 105 kPa, while the fluid temperature varied from 36.4°C to 51.0°C. Three types of flow patterns, namely slug, slug-annular transitional, and annular flows, were observed in the 90° bend at reduced gravity conditions. The typical characteristics of these regimes are shown in Fig.2.



 $U_{SL}=0.09 \text{m/s}$  $U_{SG}=1.78$ m/s  $U_{\rm SL}=0.44\,{\rm m/s}$  $U_{SG}=2.09$  m/s  $U_{\rm SL}=0.40$  m/s  $U_{SG}=11.1 \text{m/s}$ (b) Transition UsL=0.09m/s  $U_{SG}=21.6 \text{m/s}$ UsL=0.13m/s Usg=21.9m/s UsL=0.20m/s Usg=23.5m/s



In general, the slug flow is characterized by the bullet-shaped bubbles with a length of more than two times of the inner diameter, moving along in a position closer to the inside of the bend due to the influence of the centrifugal acceleration (Fig.2(a)). Short bullet-shaped bubbles have irregular shape with an obvious bulge towards the outside of the bend. Striations on the gas-liquid interface, which always spread from the inside to the outside at an acute angle to the forward direction, are observed in some conditions. It is also observed that the bubbles have an imposed rotation. Such phenomena may arise from the liquid secondary flow, which will be discussed later. Long bubbles become sharp-nosed and lean toward the inside of the bend when they move through the bend.



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Their rears are slanted toward the inside wall to form sharp corners, off which small bubbles would come. Immediately after the bend, however, a smooth hemispherical front of gas bubbles is observed again. A slight slant toward the opposite side of the pipe, which is caused by the separation of the liquid flow near the outlet of the bend, is also observed at the same position. The recovery to the smooth flat rear also occurs quickly when the bubbles enter the downstream tangent.

With the gas velocity increasing, a larger number of small bubbles come off the sharp rear corner of a long bubble and the flow pattern will become a frothy slug-annular transitional flow, as shown in Fig.2(b). This is only one way of the transition from slug flow to slug-annular transitional flow in the bend, which occurs in the case of large liquid flow rates. For the case of a small liquid flow rate, there is another way of the transition in which the slanted rear will touch the sharp nose of the succeeding bubble but no coalescence occurs through the bend.

Annular flow in the bend has a similar appearance as that observed in straight pipes at reduced gravity conditions (Fig.2(c)). There is no obvious difference of the liquid film thickness around the periphery of the bend owing to the strong gas inertial effect. Detailed analyses of the video images show that the gas core usually has an imposed rotation, which can be inferred from the obvious striations on the gasliquid interface spreading from the inside to the outside at an acute angle to the forward direction. This phenomenon is much more obvious at a larger liquid flow rate as compared to the case of a smaller liquid flow rate. As mentioned above, similar structures are also observed in the slug flow. The reason for such phenomena is discussed here.

Because of the presence of a gas core or long bullet-shaped bubble, the liquid flow is localized in the thin film adjacent to the wall. Therefore, in the case of two-phase flow in bends, the liquid secondary flow caused by the centrifugal acceleration cannot keep the symmetrical pattern of the streamlines with a pair of vortices as those in the single-phase flow. A natural alternative is a helical shape of the liquid streamlines. This flow structure is indicated by the obvious striations on the gas-liquid interface, which always spread from the inside to the outside at an acute angle to the forward direction. It can be shown that this kind of liquid secondary flows will lead to the shear stress acting on the gas-liquid interface in the circumferential direction and then cause rotation of the gas core.

Gardner & Neller <sup>[11]</sup>, who reported the phase distribution of bubble flows in bends at the normal gravity condition, also observed this type of flow structures, but provided incorrect physical images with a pattern of the liquid streamlines symmetrical about the longitudinal section in the plane of the bend. According to their interpretations, the liquid entering the bend hits the outside of the bend and then diverges around the walls towards the inside. The liquid flowing around the two sides of the periphery of the bend eventually meet and pile up to form deep turbulent rivulets. If their explanations were correct, the striations on the gas-liquid interface would spread from both the inside and the outside to opposite sides at an acute angle to the forward direction. The facts, however, are not so. It is found in the present study that the striations always spread from the inside to the outside at an acute angle to the forward direction.

According to the above observation, a flow pattern map of two-phase flows in the bend is plotted in Fig.3 using the gas and liquid superficial Weber numbers as the abscissa and ordinate. The predictions using the empirical Weber number model (developed initially based on straight pipe data using the same facility  $^{[12,13]}$ ) are plotted in Fig.3 for comparison. The semi-theoretical Weber number model proposed by Zhao & Hu<sup>[14]</sup>, in which the transitional flow is not considered as an independent category of major flow patterns of two-phase flows at reduced gravity conditions, is also plotted in the same figure.



Fig.3 Flow pattern map of two-phase flow in a 90° bend at reduced gravity

The data points with the cross symbol (+) in Fig.3 indicate that different flow patterns are observed in the bend compared to those in the vertical straight pipe with a different inner diameter of 9.5 mm. No observation was made in the upstream tangent with the same inner diameter of 12.7 mm in the experiments, it is unclear whether the same flow patterns occur in the upstream tangent at the same conditions or not. Such differences, however, may be caused by a slight increase in the inner diameter, which would cause the velocities of the two phases to decrease and their inertial effects to be weakened. Considering the dependence of the superficial velocity on the inner diameter, the Weber number will be varied inversely as the cube of the inner diameter. Thus the Weber number in the bend will be less than a half of that in the vertical straight pipe for the same experimental run. This is verified by an excellent agreement between the experimental data and the prediction using the Weber number model. No shift of transition boundaries occurs in the present work. Therefore, compared to those in straight pipes, only the apparent characteristics of the flow patterns in bends may be changed while the dynamic condition for them may not be changed, at least in the present range of parameters.

The reasons may be as follows: At first, the large gas inertia compared to the centrifugal acceleration in the present cases may diminish the effect of the latter. Secondly, the short length-to-diameter ratio of the bend will allow insufficient time for flow pattern transition to occur when the two-phase mixture flows through the bend. In addition, the upstream tangent has a length-to-diameter ratio of 46. Then the influence of the inverted U bend on the flow patterns at the inlet of the bend can be neglected, and then the flow patterns at the inlet of the bend can be considered as fully developed.

Berg et al.<sup>[9]</sup>, focusing on the bubble-slug transition, also reported similar conclusions. They found that the bubble-slug transition in both straight pipe and 90° bend can be represented by the drift-flux model, namely  $U_{\rm SL} = U_{\rm SG}(1 - C_0\alpha_{\rm cr})/C_0\alpha_{\rm cr}$ . The transitional value for  $C_0\alpha_{\rm cr}$  was found to be  $0.44\pm0.03$ in their experiments in the vertical straight pipe, which is in good agreement with Colin et al.<sup>[2]</sup> and Jayawardena et al.<sup>[15]</sup>. It ought to be pointed out here that the transitional value is determined by the pipe diameter, surface tension, densities and viscosities of gas and liquid phases<sup>[2,15]</sup>. Flow patterns in their 90° bend were superimposed by an air-water separation caused by the centrifugal acceleration. The increased bubble packing near the inside wall of the bend may favor the slug creation. However, the possible shift of the bubble-slug transition cannot be identified clearly. They explained that the reason lies in the short duration of flow through the bend as compared to the duration of coalescence between bubbles.

In the end, the possible boundary between bubble and slug flows in the present case is examined. According to Colin et al.<sup>[2]</sup> and Jayawardena et al.<sup>[15]</sup>, the value for  $C_0\alpha_{\rm cr}$  will be found to range between  $0.42\sim0.54$ . In our experiments, the minimum value for  $C_0\alpha$  is 0.67, which is greater than the transitional value. Based on the discussion of Berg et al.<sup>[9]</sup>, it may be assumed that no bubble flow can be observed. The experimental observation confirmed it.

#### 4 CONCLUSIONS

A set of experimental data of two-phase flow patterns in a  $90^{\circ}$  bend with an inner diameter of 12.7 mmand a curvature radius of 76.5 mm at microgravity are reported. It is found that:

- (1) A short bullet-shaped bubble always has a much irregular shape with an obvious bulge toward the outside of the bend. Long bubbles in the slug flow become sharp-nosed and lean toward the inside of the bend when they flow through the bend. Their rears are slanted toward the inside wall to form sharp corners, off which small bubbles may come.
- (2) Transition from the slug to the slug-annular transitional flow occurs in two ways. At a large liquid flow rate, a large number of small bubbles coming off the sharp rear corner of a long bubble lead to a frothy slug-annular transitional flow. In contrast, the slanted rear at a small liquid flow rate may touch the sharp nose of the succeeding bubble with no coalescence through the bend. And then transition occurs.
- (3) The bullet-shaped bubbles in the slug flow and the gas core in the annular flow usually exhibit imposed rotation, which can be inferred from the obvious striations on the gas-liquid interface spreading from the inside to the outside at an acute angle to the forward direction. It may arise from the secondary liquid flow in the bend, which is modified by the presence of the gas phase.
- (4) No shift of transition boundaries is observed in the present parameter range. The experimental data agree well with the predictions by Weber number models.

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