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Effect of the Gravity Forces on Flow Pattern and Frictional Pressure Drop in Two-Phase, Two-Component Flow

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Abstract : Experimental data on the effect of the variable gravity magnitude, namely microgravity, normal gravity and hyper-gravity, on flow pattern and frictional pressure drop were obtained during co-current air-water flow in a horizontal tube. The flow patterns were found to depend strongly on the gravity magnitude and certain flow pattern were found to depend on the gas superficial velocity. The effect of the gravity magnitude had an effect on the frictional pressure drop only at low flow rates. The present data are used to evaluate some of existing flow pattern transition and pressure drop models and correlations.

Key words : Microgravity, Two-Phase flow, Flow Pattern, Frictional Pressure Drop

Nomenclature

C	Chisholms parameter; [-]
G	Gas-phase
g	Earth's gravity; [m/s^2]
j	Superficial velocity; [m/s]
L	Liquid-phase
TP	Two-phase
X	Lockhart-Martinelli parameter; [-]
ΔP_f	Frictional pressure drop; [Pa/m]
ρ	Density; [kg/m^3]
σ	Surface tension; [N/m]
Φ_L	Two-phase multiplier, ratio of two-phase to liquid single-phase pressure drop; [-]

1. Introduction

Two-phase flows occur in many industrial applications, including power generation plants, chemical plants, pipelines, geothermal energy systems, steam generators, air conditioning and refrigeration systems, heat exchangers, and cooling channels of nuclear reactors. Two-phase loop systems using its latent heat capacity can meet the increasing power requirements and are well suited to thermal management systems of future large space applications, due to its abilities to handle large heat loads and to

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provide them at uniform temperatures regardless of the changes in the heat loads. A number of experimental works [1~4] have been conducted on gas- liquid two-phase flows under microgravity using flight or drop-tower. However, two-phase flow characteristics differ when the gravity changes, due to the difference of buoyancy between two phases. Theoretical efforts[5], [6] to develop the two-phase flow pattern transition maps treating the gravity as a parameter have been presented. In order to design the reliable space thermal management systems applying a two-phase flow, however, systematic studies on the effect of gravity on the two-phase system factors are essential to the designers of such systems, because they are deeply interrelated, namely such as flow patterns and frictional pressure drop. Nevertheless, very little fundamental research on those exists in the literature, due to the limited access to such environment, and the high costs associated with it.

Experimental researches were therefore performed on effects of gravity on the two-phase flow characteristics. Some results are obtained from the experiments using the flight producing μg and 2g conditions and on ground with the identical flow conditions. The experimental results obtained at μg, 1g and 2g conditions are compared with some of the existing flow pattern transition and frictional pressure drop models and correlations, and the differences and similarities between these flow characteristics at three gravity levels are also discussed.

2. Experimental facilities and procedures

The present experiments were carried out onboard MU-300 flight and at normal gravity conditions. Water and air are used as the working fluids. Water is forced by the gear pump from the separator tank, and then it flows to the mixing section through the water flow meter and back to the separator tank. Water flow rate is controlled by adjusting the rotational speed of the gear pump driven by an electric motor. Air is supplied from the compressed air cylinder, passes through the air flow meter, sonic orifices and mixed with liquid in the mixing section. Air flow rate is controlled by passing the air through sonic orifices depending on the flow rate desired. The mixed two-phase air-water mixture exits the mixing section into the test section through the flow development section of 500mm length. The test section with water-filled viewing box for flow pattern observation is a transparent acrylic horizontal adiabatic pipe of 10mm ID, 600mm length. The flow patterns are recorded by the high-speed video camera. The differential pressure drop is measured by the differential pressure transducers with pressure tap attached to both ends of the test section. And these experiments are conducted within the experimental ranges of liquid and gas superficial velocities, j_L=0.1~2.6m/s and j_G=0.03~21m/s, respectively.

The μg and 2g data were collected on board MU-300 parabolic aircraft. A typical parabolic maneuver of MU-300 flight is shown in figure 1. The parabola begins with the hyper-gravity portion, where acceleration levels are 2±0.1g for 20 seconds. The microgravity period lasts about 20 seconds during which time the pilots maintain the acceleration level, $g_z=0.01\pm0.01g$ (g is Earth's gravity), followed by the recovery portion of the parabola of 1.5g for 10 seconds. The parabola ends with approximately 120 seconds of level flight before the next parabola sequence is started. 11 parabolas are flown each day (a total of 57 parabolas). The terrestrial tests are also conducted with the identical flow direction and conditions.

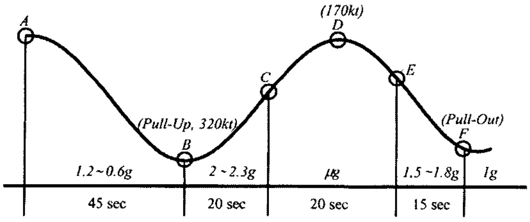


Fig. 1 Typical MU-300 parabolic flight.

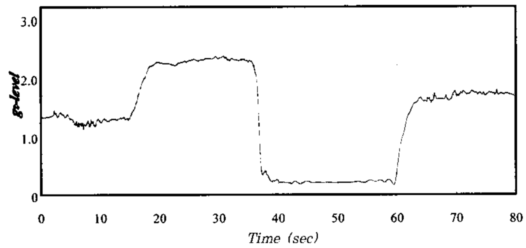


Fig. 2 Gravity signal during data collection. period of a typical parabola.

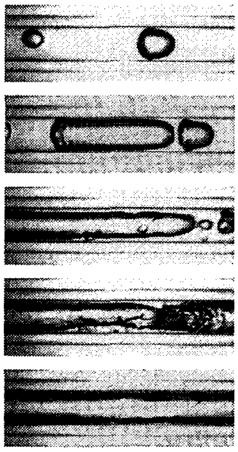
The level flying periods between the parabolas were used to set the liquid and gas flow rates. The data collection was started ten seconds prior to the pull up phase and continued until the approximately ten seconds after the pull out portion of the parabola. This allowed hyper-gravity and microgravity data to be collected in the same file without changing any parameters. The gravity signal during the data collection period of a typical parabola is shown in figure 2.

3. Results and discussion

3.1 Flow patterns

The development of a flow pattern map at μg is needed to predict the flow pattern transitions, as well as the flow present in the conduit at pre-determined liquid and gas flow rates. Flow observations were collected over a wide range of liquid and gas flow rates. Visual observations indicated that the two-phase flow patterns underwent a significant change when the gravity level varied from 2g to μg conditions. A series of prints of frames at different gas and liquid velocities were selected to convey the basic flow pattern observations that were present in the horizontal observation test section. These are shown in figure 3. Bubbly flow, as shown in the first frame, has large spherical bubbles, which diameter is approximately equal to the pipe inside diameter, that tend to flow along the pipe centreline. Taylor bubble flow is different from slug flow in that the nose is smooth, and it has a bullet-shaped appearance with no or little small bubbles in the liquid slugs. The transition from slug to annular is called semi-annular flow, in which case the liquid is flowing in the form of a film at the pipe wall, and the gas phase is flowing at the center with frequent appearances of frothy type slugs in it. Annular flow has similar appearance to that at 1g, except that the interface between the phases is relatively smoother under μg. But the stratified flow occurred at 1g and 2g conditions was not observed under μg. On the other hand, for 1g and 2g conditions, the flow patterns of stratified, bubble, plug, semi-annular and annular flow were observed.

A flow pattern map was developed based on the gas and liquid superficial velocities with μg experimental data, together with only the flow pattern transition results for 1g and 2g conditions. This is shown figure 4. The thicker-solid lines in the figure indicate the transition boundaries from one to another flow patterns for all three g-levels. All the transition boundary lines from bubbly to Taylor bubble flow (TB or plug flow) appear a positive slope of 1 meaning constant values of void fraction α. The flow pattern transitions were found to occur at $j_L=1.5j_G$ for μg, $j_L=5j_G$ for 1g, and $j_L=7.5j_G$ for 2g, respectively. At μg conditions, bubbles are flowing with almost the same speed as the adjacent liquid phases, thus the probability of coalescence when bubbles contact each other decreases. This produces the result that the transition at mg in this region occurs at the higher void fraction value than that at 1g and 2g. It implies that the gravity plays a significant role in the transition mechanism. For the transition from Taylor bubble (TB or plug flow) to slug flow, the transition boundaries in all the three g-levels lied at the same line of approximately $j_G=1.0$ m/s. It can be also estimated by gas Weber number defined as $W_G=\rho_G j_G^2 D/\sigma$, and calculating it with the value of $j_G=1.0$m/s gives $W_G=0.16$. For the transition from slug to semi-annular flow, the transition under μg occurs at the line of $j_L=0.12j_G$, while it occurs at $j_G=3.7$ m/s for 1g, $j_G=7.47$ m/s for 2g. As the magnitude of gravity is increased, due to the increase in buoyancy force, it becomes not only difficult to form the liquid slugs which bridge the tube, but also to reach at the maximum packing void value of $\alpha_{max}=0.52$ implying an upper limitation on the flow pattern transition. These lead to the result that the transition line for 2g lies at the higher j_G than that for 1g. In the transition from semi-annular to annular flow, the transition boundary lines for all the three g-levels are showed


(a) Bubbly flow

(b) Taylor bubble flow

(c) Slug flow

(d) Semi-annular flow

(e) Annular flow

Fig. 3 Two-phase flow patterns at μg.

to be located at the same line of $j_L=0.12j_G$ ($\alpha_t=0.8$). It is the reason that the region is dominated by the inertia forces.

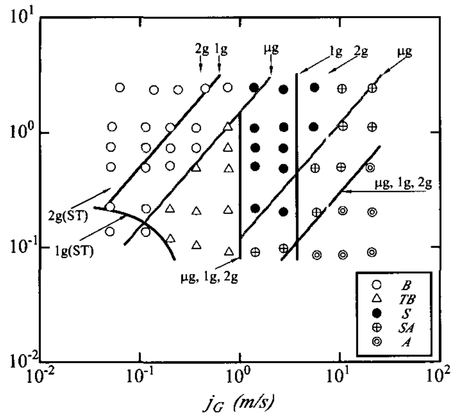


Fig. 4 Flow pattern map.

3.2 Frictional pressure drop

In order to optimize the design of a system with two-phase flow, the pressure drop associated with flow patterns has to be accurately predicted. When gravitational forces are changed, the behaviour of the flow is different. The resultant effects on the two-phase pressure drop components must be analyzed. The total pressure drop in two-phase flows can be expressed as the sum of frictional pressure drop, gravitational pressure drop and accelerational pressure drop. For fully developed, adiabatic, horizontal orientation and steady-state flow in a pipe with a uniform cross section, the gravitational and accelerational pressure drop component can be ignored. The total pressure drop measured in this experiment can be therefore estimated as only the frictional pressure drop:

$$(dp/dz)_F = (dp/dz)_{TOTAL} \tag{1}$$

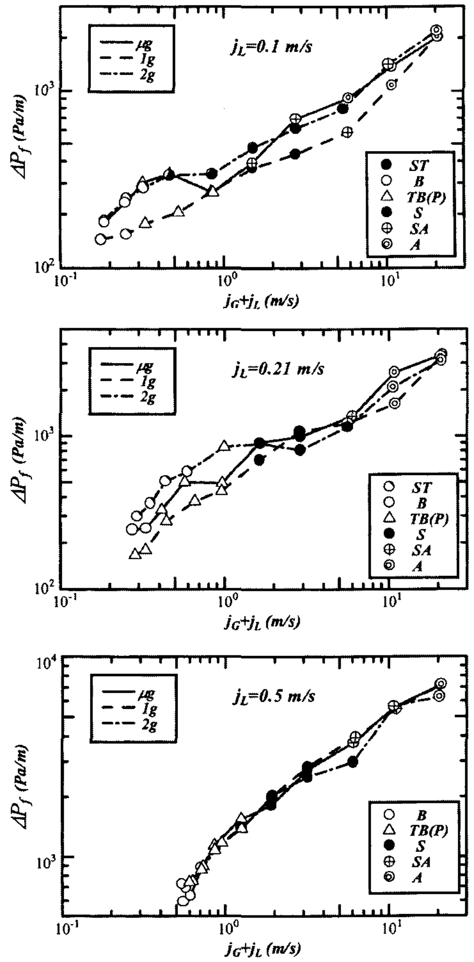


Fig. 5 Frictional pressure drops obtained at μg, 1g and 2g.

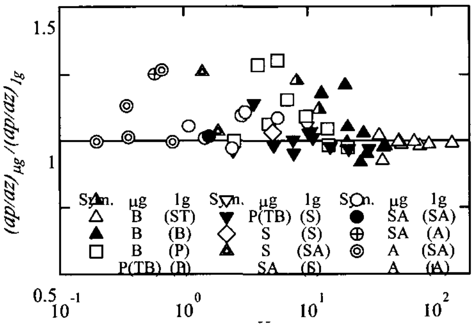


Fig. 6 Ratio of frictional pressure drop for μg to that for 1g.

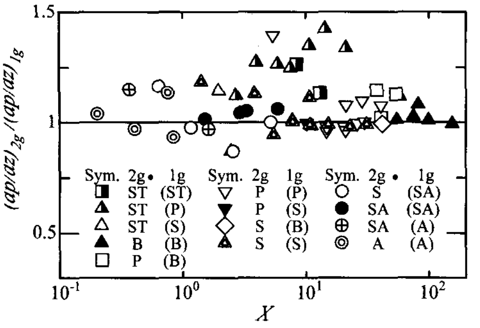


Fig. 7 Ratio of frictional pressure drop for 2g to that for 1g.

Some of experimental frictional pressure drop data under μg are plotted in figure 5 using the mixture velocity j_T (j_G+j_L). Corresponding flow patterns are also indicated on each data point. As can be seen in the figure, at a constant j_L, the frictional pressure drop increases, as the mixture velocity increases, except for the laminar flow region of $j_L \leq 0.21$ m/s. However, at a constant j_G, it appears that the increasing j_L results in a significant increase in the frictional pressure drops in all cases for all flow patterns. On the other hand, as can be seen in the figure, when $j_L=0.5$ m/s, the differences between frictional pressure drops at three g-levels are insignificant. However, in case of $j_L \leq 0.21$ m/s, the differences between the frictional pressure drop at 2g and μg that at 1g were found to be relatively significant. The result is to be unexpected. In general, if the slip ratio is reduced, then the interfacial friction factor should be also reduced, and consequently the pressure drop should be rather smaller. However, the unexpected result could be explained by the reason that the frictional pressure drop might be influenced more strongly rather by the difference in the flow pattern induced by the change in gravity than by the difference in the slip ratio. It is namely the reason that for bubble and Taylor bubble flows at μg, the velocity of the liquid phase between the tube wall and bubbles is accelerated due to the bubble or Taylor bubble travelling along the tube centerline with nearly the same size to the tube inside diameter, although those at 1g and 2g move along the upper wall. Moreover, even on the same annular flow region at very high flow rates, the significant differences are occasionally showed. Although they could be due to the influence of the difference in the distribution in a conduit, thickness and wave roughness of the annular liquid film, it should be more fully studied on those in future.

The ratio between frictional pressure drop values at μg and 1g is shown in figure 6 by using the Lockhart-Martinelli parameter X defined in equation (3). The figure appears that the maximum ratio of the frictional pressure drop at 1g to that under μg is approximately 1:1.3 for just the region of $j_L \leq 0.21$ m/s, while it shows no significant difference for the turbulent flow region of $j_L \geq 0.5$ m/s.

Comparisons between 1g and 2g results follow generally the same trend, as can be seen in the figure 7, although the resulting reasons were different from those between μg and 1g. Comparisons of the movie films on the stratified and plug flows at 1g and 2g confirmed that the stratified flow at 2g has a lower liquid phase in depth and a rougher interface, as well as the plug flow at 2g has a longer gas plug in length and a rougher interface, as respectively compared to such flow patterns at 1g. In case of the stratified flow at 2g, the increase in the velocity of the liquid phase in the reduction flow area causes the wave amplitude in air-water interface to increase, consequently frictional pressure drop to increase. These would produce the difference between frictional pressure drop values at 1g and 2g stratified flow. Comparisons for the plug and slug flows at 1g versus the stratified flow at 2g show significant difference. This may also be due to the influence of the roughness in the interface by the accelerated liquid phase, judging from the fact that the difference in the ratio differs by the difference in the degree of the roughness on the interface, even on between 1g and 2g plug flow. However, it should be also noted that the roughness might be induced by the flight its vibration and the residual g-levels in x, y and z direction during flying. The maximum ratio of the frictional pressure drop at 1g to that at 2g is approximately 1:1.45. However, the differences between the frictional pressure drop values at all three g-levels are within ±11% for the turbulent flow region of $j_L \geq 0.5$ m/s, regardless of the change in gravity.

The experimental multipliers Φ_L for μg, 1g and 2g conditions are plotted in figures 8, 9 and 10 using the Lockhart-Martinelli parameter X. The liquid two-phase multiplier Φ_L and the Lockhart-Martinelli parameter X are defined as

$$\Phi_L = [(dp/dz)_{TP}/(dp/dz)_L]^{0.5} \tag{2}$$

$$X = [(dp/dz)_L/(dp/dz)_G]^{0.5} \tag{3}$$

where $(dp/dz)_L$, $(dp/dz)_G$ are the single-phase liquid and gas frictional pressure gradients calculated using the liquid and gas flow rate alone, respectively.

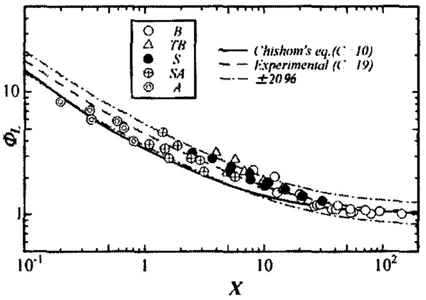


Fig. 8 Comparison of frictional pressure drop at μg with Chisholm's correlation.

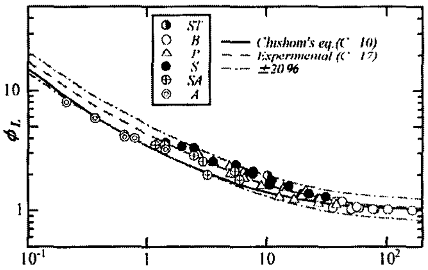


Fig. 9 Comparison of frictional pressure drop at 1g with Chisholm's correlation.

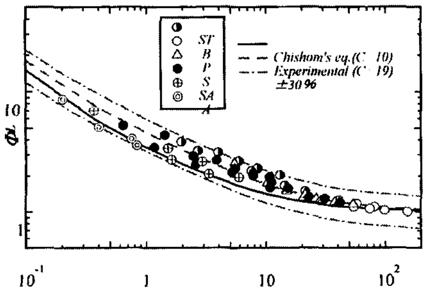


Fig. 10 Comparison of frictional pressure drop at 2g with Chisholm's correlation.

And approximating these relationships, Chisholm's equation is expressed by

$$\Phi_L = \left[1 + C/X + 1/X^2\right]^{0.5} \tag{4}$$

where C is a parameter first introduced by Chisholm. The thick-solid line in the figure is calculated by using the value of $C=10$ (liquid-gas: turbulent-laminar) in equation (4). The broken-line also indicates the value of C determined by the least-square approximation method with the actual values of the multiplier Φ_L based on frictional pressure drop data under μg. The values of C for the laminar region ($Re<1500$) and the turbulent region ($Re>1500$) were determined to be C=22, 15 for μg; C=23, 15 for 2g, respectively. However, the values of C estimated over all the regions at each g-level were as followings: $C=19$ (the accuracy of ±20%) for μg; $C=17$ (±20%) for 1g; $C=19$ (±30%) for 2g, respectively.

4. Conclusions

In order to investigate the effect of the gravity forces on two-phase flow patterns and frictional pressure drop, several experiments were performed on board MU-300 flight and at normal gravity. The results obtained in this study are as followings:

1. In the laminar region of $j_L \leq 0.21$ m/s, the effect of the gravity change on the flow patterns and the frictional pressure drop was relatively significant.
2. The maximum ratio of the frictional pressure drop at 1g to that under μg was about 1:1.3. It was due to the difference between the flow patterns at 1g and μg .
3. In the turbulent region of $j_L \geq 0.5$ m/s, the effect of gravity change on the frictional pressure drop was insignificant.
4. In the Chisholm's correlation, the value of C was estimated as 19 for the microgravity frictional pressure drop.

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