Flow Characteristics of Gas-Liquid Two-Phase Annular Flow under Microgravity* (Experimental Results Utilizing a Drop Tower)

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In order to predict various phenomena related to flow and heat transfer in space, it is necessary to carry out experiments under microgravity. The present work is concerned with the characteristics of gas-liquid two-phase annular flow under microgravity condition utilizing a drop tower. The experiments were carried out in a vertical transparent acrylic tube of 10.5 mm I.D. and 200 mm length, using a mixture of gaseous nitrogen (GN_2) and water as the working fluid, in an annular flow region. The mean void fraction, pressure drop and liquid film thickness under microgravity were obtained and compared with the results of a ground test. It was found that the roughness of the liquid film surface was less and the mean liquid film thickness became greater under microgravity than under normal gravity.

Key Words: Pipe Flow, Multiphase Flow, Microgravity, Annular Flow, Void Fraction, Pressure Drop, Liquid Film Thickness

1. Introduction

In satellites and space stations, and further the lunar base and space factory, which might be realized in the future, it becomes a great problem how the exhausted heat is collected and radiated to space. Heat pipes and single-phase liquid flow loops have been so far used as the heat removal system. However, with the recent tendency of increasing capacity and size, more and more attention is paid to two-phase flow loop management control systems. Their advantages are (i) the total system weight can be reduced because of the decreasing heat transfer area and flowrate due to the increase of the heat transfer

coefficient by utilizing the phase change phenomenon of the working fluid, and (ii) the temperature is easy to control by means of saturated-pressure control.

The heat and mass transfer characteristics of the two-phase flow loop system under microgravity condition are considered to be different from those under ground condition because of microgravity, but they have not yet been clarified fully.

Heppner et al.⁽¹⁾ showed that the behavior of two-phase flows under microgravity differed greatly from those under 1G. Dukler and Colin et al.⁽²⁾⁻⁽⁴⁾ investigated void fraction, pressure loss, flow pattern, and so on under microgravity from experiments of trajectory flight using a Learjet and of drop towers. In Japan⁽⁵⁾⁻⁽⁷⁾, experiments under microgravity have been carried out using airplanes and drop towers, and the transition condition of the flow pattern map and pressure losses have been partly obtained.

However, the number of data in all experiments is limited, and especially there are very few data in the region of annular flow. Also, they were dealt with from the macroscopic viewpoint and the microscopic structure of the flow were not discussed. The transfer characteristics of momentum, heat, and mass are

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dependent on the interfacial structure between gas and liquid. This sort of investigation has not yet been made under microgravity. In this study, in order to make clear the flow characteristics of unheated two-component gas-liquid annular flow under microgravity environment like space, not only the flow transition and pressure losses but also the liquid-film structure were investigated mainly in the annular flow region under microgravity, using a drop tower 10 m in height.

2. Main Symbols Used

- C : Coefficient [Eq.(4)]
 C_0 : Distribution parameter [Eq.(1)]
 c : Wave velocity (m/s)
 D : Pipe diameter (m)
 f : Frictional coefficient
 j : Volumetric velocity (m/s)
 ΔP : Pressure loss (Pa)
 Re : Reynolds number
 r : Pipe radius (m)
 u : Velocity (m/s)
 V_{ci} : Drift velocity (m/s)
 X : Lockhart-Martinelli parameter [Eq.(4)]
 $\Delta z, z$: Distance, Length (m)
 α : Void fraction
 δ : Liquid-film thickness (m, mm)
 λ : Pipe's frictional coefficient
 ρ : Density (kg/m³)
 τ_i : Shearing stress (N/m²)
 ϕ : Two-phase flow friction loss parameter [Eq.(2)]
- Subscripts
 av : Average
 B : Continuous-phase
 G : Gas-phase
 i : Gas-liquid interface
 L : Liquid-phase
 max : Maximum
 TP : Two-phase

3. Experimental Apparatus

The schematic flow sheet of the experimental apparatus is shown in Fig. 1. The working fluids are water as the liquid phase and gaseous nitrogen as the gas phase. Water is fed into the mixing section ③ (water flows in from the circumference of the tube and gaseous nitrogen flows in the central core) by the gear pump ⑫ via the separation tank ⑬ having a stainless-steel mesh at the bottom so that the gas-liquid separation is made fully. The two-phase fluid made in the mixing section ③ flows into the vertical test section 10.5 mm in inner diameter and 192 mm in length, where differential pressure loss and void frac-

Fig. 1 Schematic diagram of experimental apparatus

Fig. 2 Detail of test section (unit: mm)

tion are measured. Also, visible observation of the flow behavior is made by a CCD camera and is recorded by a video cassette recorder. The fluid temperature is measured by the thermocouple ⑩ at the exit of the pump and the pressure is measured by the differential pressure sensor ②. The probe for the measurement of the liquid-film thickness is made of two stainless-steel wires having a diameter of 0.6 mm and a length of 5 mm. It is installed at intervals of 3 mm towards the center of the tube^{(5),(6)}. The liquid-film thickness is obtained from a curve calibrated, in advance, measuring the resistance value between the fine wires by the

Fig. 3 Experimental apparatus

Fig. 4 Flow pattern under μG Fig. 5 Flow pattern map under μG

Wheatstone bridge method. The gas and water flowrates are controlled by the secondary pressure ⑥ of the controll valve and the motor voltage of the gear-pump, respectively, and are measured by the gas flowmeter ④ and the water flowmeter ⑨. All of them

Table 1 Experimental ranges

Fluid	j_{GL} (m/s)	Re_{GL}
GN ₂	1.2~19.0	$4.7 \times 10^3 \sim 2.0 \times 10^4$
Water	0.040~0.488	$4.3 \times 10^2 \sim 5.8 \times 10^3$

are installed on a rack $400 \times 400 \times 400^H$ mm in size as shown in Fig. 3, and the rack is then placed in an inner capsule. The free drops in the drop tower (the duration is about 1.4 s, the microgravity environment is $10^{-2} - 10^{-3}G$) are carried out 40 times in total for 7 days in the experimental ranges (for the most part in the annular flow region) of Table 1. Also using the same apparatus, the ground test is carried out for comparison between microgravity and ground conditions.

4. Experimental Results and Correlations

4.1 Flow regimes

The flows under microgravity in these experimental ranges were of three patterns, that is, (i) plug flow, (ii) semiannular flow, and (iii) annular flow, as shown in Fig. 4. The flow patterns are plotted against the respective superficial velocities j_G , j_L in Fig. 5, where the bold line shows the transition regime from the semiannular flow to the annular flow under 1 G. It occurs at the j_G value of 7 to 8 m/s independent of j_L , although Taitel et al.'s equation⁽⁸⁾ gives approximately 14 m/s and Weisman et al.'s equation⁽⁹⁾ gives 5 to 8 m/s. On the other hand, the transition under microgravity occurs at a value of $j_G = 4$ m/s independent of j_L , and it was shown that it shifts to a lower j_G .

In the following sections, the data in the annular flow regime are adjusted.

4.2 Void fraction

The mean liquid-film thickness is obtained from the output of the amplifier for the measurement of the bridge resistance connected to the void fraction probe and then the void fraction is calculated. The void fraction is correlated by the following equation based on the drift flux model⁽⁸⁾ and is shown in Fig. 6.

$$u_c = \frac{\langle j_G \rangle}{\langle \alpha \rangle} = C_0 \langle j_G + j_L \rangle + V_{Gj} \quad (1)$$

The drift velocity V_{Gj} can be obtained from the difference of the buoyancy force between the two phases, but under microgravity it was almost null. In the figure, the experimental results which we obtained in the annular flow region in the airplane⁽⁵⁾ are shown by the symbol $\triangle$ as well as the above results ($\circ$) and the results under 1 G with the same apparatus (∇). The solid and broken lines in Fig. 6 are the asymptotic straight lines obtained for the experimental results under both μG and 1 G. Under 1 G shown by a broken line, the distribution parameter C_0 is 1.04 and V_{Gj} is 1.07 m/s. Under μG shown by a solid line, V_{Gj} is null

Fig. 6 Correlation by drift-flux model

Fig. 7 Friction pressure loss

and C_0 increases to a value of 1.33. It is shown that the mean void fraction under μG decreases under the same values of j_G and j_L , that is, the mean annular liquid-film thickness increases.

4.3 Frictional pressure losses

The frictional pressure losses are shown against $(j_G + j_L)$ in Fig. 7 in the annular flow region under both μG and 1 G using the same experimental apparatus. The points plotted show the results under μG and the broken lines show the results under 1 G. It is shown that the frictional pressure losses under μG in the annular flow region show a little different tendency from those under 1 G in the range of $(j_G + j_L) = 5 \sim 10$ m/s, but there is not a very great difference between 1 G and μG .

The frictional pressure losses are arranged by the following parameter given by Martinelli and compared.

$$\left(\frac{\Delta P}{\Delta z}\right)_{TP} = \left(\frac{\Delta P}{\Delta z}\right)_L \phi_L^2 \quad (2)$$

$$X = \sqrt{\left(\frac{\Delta P}{\Delta z}\right)_L / \left(\frac{\Delta P}{\Delta z}\right)_G} \quad (3)$$

Fig. 8 Correlation by L-M method

where $(\Delta P / \Delta z)_{TP}$ denotes the pressure loss in the two-phase flow, and $(\Delta P / \Delta z)_L$ denotes the pressure loss when only the liquid phase or the gas phase flows in the pipe. Figure 8 shows the correlation between Martinelli's parameter X and the frictional pressure loss multiplier coefficient ϕ_L , where the data under μG are shown for two ranges of $(j_G + j_L)$ greater or less than 10 m/s. The solid and broken lines in Fig. 8 show the least-square approximation curves given by the following Chisholm equation.

$$\phi_L^2 = 1 + \frac{C}{X} + \frac{1}{X^2} \quad (4)$$

The value C , Chisholm's parameter, is 14 under μG . It is 12 under 1 G, which is the same as in the case where the liquid phase is laminar and the gas phase is turbulent. Judging from this value, ϕ_L is greater by 5 to 10% under μG than that under 1 G. However, there is no great difference, considering the scatter of the experimental data.

4.4 Liquid-film structure

In the annular flow regime, the structure of the liquid-film flowing along the tube wall, such as the thickness, amplitude, and frequency of the liquid-film, plays a great role in the heat and flow characteristics. The liquid-film thickness δ is shown in Fig. 9 (a) and (b), where the horizontal axis is the length z , which is the real time multiplied by the mean liquid-film velocity calculated from the liquid-film thickness $\delta^{(6)}$. Figure 9 (a) shows the results under μG and Fig. 9 (b) shows those under 1 G. They both show the state of the liquid-film thickness against the change of j_G at an almost constant value of $j_L \approx 0.4$ m/s. It can be recognized that under μG the liquid-film is smoother and that the continuous thickness of the liquid film becomes greater than under 1 G. Furthermore, the amplitude of the liquid-film wave is found to be lower with an increase of j_G .

Next, the maximum liquid-film thickness $\delta_{\max}$, the continuous layer thickness δ_B , and the mean liquid-film thickness $\delta_{av}^{(9)}$ are shown against Re_c

Fig. 9 Effects of j_G on liquid-film thickness

($=u_G \times D_G / \nu_G$) in Fig. 10 (a) to (c) with the value of $Re_L (=j_L \times D / \nu_L)$ as a parameter. Respective points plotted denote the results under μG . The results under 1 G are shown asymptotically by broken lines to avoid the complexity of the figure. Here, the vertical axis denotes the dimensionless value obtained by dividing the liquid-film thickness by the radius of the test pipe, $r = 5.25$ mm. The dimensionless maximum liquid-film thickness $\delta_{\max}/r$ is in the range of 0.15 to 0.3 and has a weak tendency to decrease with an increase of the gas velocity in a similar way to that under 1 G. It is found that although it increases with the value of Re_L under 1 G, it is not very dependent on Re_L under μG . This means that under μG the disturbance wave with a greater wave height is difficult to generate. On the other hand, the dimensionless liquid-film thickness δ_B/r is approximately 0.11, which is 10 times as large as the value of δ_B/r , 0.012 to 0.03, under 1 G. Also, it is found that it does not vary very much with both the gas and liquid velocities

Fig. 10 Liquid film thickness

Fig. 11 Frictional coefficient of gas-phase in annular flow region

under μG . It is evident that the liquid-film thickness under μG is 2 to 5 times as thick as that under 1 G.

4.5 Interfacial friction

The gas phase in the core of the annular flow region has the resistance due to the liquid-film surface. The frictional pressure losses at the gas-liquid interface will be discussed below. As for the steady annular flow, it is assumed that there are no liquid droplets in the gas core, and the following equation holds for the gas phase.

$$\left(\frac{\Delta P}{\Delta z}\right)_g = \frac{4\tau_i}{D_g} \quad (5)$$

Considering the gas core flow to be the same as the pipe flow, the following is given.

$$\tau_i = f_g \frac{1}{2} \rho_g (u_g - c)^2 \quad (6)$$

Accordingly, Eq (7) is obtained.

$$\left(\frac{\Delta P}{\Delta z}\right)_g = 2f_g \frac{1}{D_g} \rho_g (u_g - c)^2 = \lambda_g \frac{1}{D_g} \frac{\rho_g (u_g - c)^2}{2} \quad (7)$$

The wave velocity is approximated to be 1.5 times the mean velocity of the liquid film⁽⁹⁾, and the core of the gas phase is given by the following equation.

$$D_c = D - 2\delta \quad (8)$$

The frictional pressure coefficient of the gas phase λ_g is shown against the ratio of the relative Reynolds number of the gas phase to the liquid phase in Fig. 11 with the liquid-film Reynolds number Re_{RG} as a parameter, where Re_L and Re_{RG} are defined as follows:

$$Re_L = \frac{u_L(4\delta)}{\nu_L} = \frac{j_L}{\alpha} \frac{aD}{\nu_L} = \frac{j_L D}{\nu_L}, \quad Re_{RG} = \frac{(u_g - c)D_g}{\nu_g} \quad (9)$$

In Fig. 11, the plotted symbols denote the results under

μG . The value λ_g becomes smaller as Re_{RG} becomes larger in a similar way to those under 1 G. But the effect of Re_L is not so great as that under 1 G. It is found that λ_g takes a value 2 to 40 times as large as that of the single phase in the smooth pipe. On the other hand, the gas core velocity u_g increases as shown in Section 4.2, owing to the decrease of the mean void fraction, that is, the increase of the mean liquid-film thickness. As a result, it can be considered that the frictional pressure losses under μG show almost the same or a little lower tendency than that under 1 G.

5. Conclusions

The void fraction, the frictional pressure losses, and the liquid-film structure in the annular flow regime were investigated under μG , using a drop tower in an unheated vertical tube with water and gaseous nitrogen as the working fluids, and were compared with those under 1 G. Summarizing the results, the following are given.

(1) The flow pattern transition from the semianular flow to the annular flow occurred at a value of j_g approximately equal to 4 m/s, independent of j_L , which is lower than that under 1 G.

(2) In a drift-flux model represented by $j_g/\alpha = C_0(j_g + j_L) + V_{Gj}$, the following values were obtained under μG : $C_0 = 1.33$ and $V_{Gj} = 0$. It was found that the void fraction was smaller than that under 1 G.

(3) The value of the Chisholm parameter, C , was 14 by least-square approximation.

(4) The maximum liquid-film thickness showed a tendency to decrease as the gas phase Reynolds number Re_g became larger but was not very dependent on Re_L . On the other hand, the mean and the dimensionless liquid film thickness were 4 to 10 times as large as those under 1 G, almost independent of Re_g .

(5) The frictional pressure losses of the gas phase, λ_g , increased with Re_L and decreased with an increase of Re_{RG} . But the effect of Re_L was not much greater than that under 1 G.

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