The Behavior of an Immiscible Equal-Density Liquid-Liquid Two-Phase Flow in a Horizontal Tube*

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Because of further increase in waste heat due to the greater power capacity of equipment for use in space, the thermal management system using vapor-liquid two-phase flow has been attracting greater attention in recent years. This has led to a decrease in system weight and pump power as a result of improvements in the heat transfer performance. However, new information on the flow and heat transfer characteristics under microgravity conditions is required. In particular, the local distribution of void fractions in the cross section under the microgravity condition is expected to differ from that on earth. The flow behavior is investigated using an equal-density liquid-liquid mixture (silicone oil and water) as the working fluid in a horizontal pipe 25 mm in ID., which causes the effect of gravity on the two phases to be diminished due to buoyancy. In this paper, the experimental results related to flow pattern, void fraction, and pressure losses are reported, and compared with other investigators' results.

Key Words: Multiphase Flow, Pipe Flow, Flow Visualization, Transition, Liquid-Liquid Two-Phase Flow, Microgravity, Flow Pattern, Pressure Drop

1. Introduction

The development of thermal management technology for waste heat has progressed in recent years because of the greater power capacity of satellites and space stations due to space development. The power output ranges from the hundreds of watts of early satellites to 18~30 kW of space shuttles and 95 kW of space stations. Greater power output is expected at lunar and Mars bases of the future. On the other hand, the thermal management system for the transport, recovery and disposal of waste heat must be designed. To date the heat pipe system and the single-phase fluid loop system have been employed.

Due to the demands of further increase of waste heat flux and transport distance, the limit of pump power and system weight, and the decrease in radiator surface area, the thermal management system using a

vapor-liquid two-phase flow loop is attracting great attention.

Under microgravity environments in space, however, the flow and heat transfer characteristics are expected to be considerably different from those on earth. To realize such microgravity environments, experiments have been carried out in drop towers and airplanes, using air-water or Freon R-114 as the working fluid⁽¹⁾⁻⁽⁶⁾. However, the duration of an experimental run is very short, several seconds to 30 seconds, and the number of experiments is limited. On the other hand, experiments on earth using equal-density liquid-liquid two-phase flow have been attempted to realize microgravity environments by diminishing the effect of the gravity between two phases by means of buoyancy force and to investigate the flow pattern and the pressure loss, because in vapor-liquid two-phase flows under microgravity environments the effect of surface tension is more prominent compared with that of gravity. Here, the flow condition under microgravity environments is simulated by realizing an equal-density liquid-liquid two-phase flow on earth. So far, the flow characteristics of immiscible liquids have been investigated for the design of tubular

* Received 28th September, 1992. Paper No. 91-1122 B

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reactors, liquid-liquid extraction equipment and pipelines for liquid transportation⁽⁷⁾⁻⁽⁹⁾. On the other hand, Wang et al.⁽¹⁰⁾ and Lovell⁽¹¹⁾ recently carried out experiments using equal-density liquids as the working fluids to clarify the flow pattern and the pressure loss under the microgravity condition, but there is little information available on such issues. From this point of view, the flow behavior, void fraction, flow pattern transition and pressure loss were investigated in this study through use of equal-density silicone oil-water (interfacial tension: 29 dyne/cm) as the working fluid.

2. Experimental Apparatus and Procedure

A schematic diagram of the experimental apparatus and the details of the two-liquid mixing section at the inlet of the test section are shown in Figs. 1(a) and (b). Silicone oil fed by a mono pump ② from the oil storage tank (0.2 m³) ① and water fed by a centrifugal pump ④ from the storage tank (1 m³) ③ flow together in the mixing section ⑦. The liquid-liquid two-phase mixture flows into the test section ⑧ which is a transparent acrylic resin tube 25 mm in ID. and 4.5 m long, and is then discharged into a separation tank ⑨. It is separated by leaving it as is for twenty-four hours and removing the milky emulsion by heating it. The flow pattern is observed and recorded on a high-speed video cassette 3.5 to 4 m downstream of the mixing section. The pressure drop is measured 3 m and 4.5 m downstream of the mixing section. Void fraction measurements are made by simultaneously closing two valves ⑩ 3.2 m and 4.3 m downstream of the mixing section. The temperature of the two-phase

flow is measured 50 mm upstream of the exit of the tube by means of a thermocouple. Each flow rate is measured by both a gear-type flowmeter ⑤ and a float-type flowmeter ⑥.

The mixing section shown in Fig. 1(b) consists of a double tube which has 600 holes each 1 mm in ID. in the inner tube. The oil flows in the inner tube and the water flows through the holes on the inner tube. The entrance distance L from the mixing section to the measuring point is such that $L/D=118$ and is already in a developed region.

The properties of each fluid are shown in Table 1. The silicone oil has a specific gravity of 0.98 and a dynamic viscosity 55 times higher than that of water. The silicone oil is chosen to match the dynamic viscosity ratio of the two-liquid mixture to that of air to water at room temperature ($\mu_{\text{water}}/\mu_{\text{air}} \approx 55$) and is almost equal to that of the vapor-liquid ratio of Freon R-11 (≈ 42 at 22°C). In this experiment, the silicone oil and water are, respectively, selected as the "liquid" and "gas" because of the higher viscosity of silicone oil. The interfacial tension is 29 dyn/cm. Here, the value of the Bond number (Bo), which is the ratio of gravity to surface tension, is $Bo = (Mg)/(\sigma D) = (\Delta\rho g D^2)/\sigma = (1000 - 980) \times 9.81 \times (25 \times 10^{-3})^2 / (29 \times 10^{-3}) = 4.2$ for the silicone oil and water mixture against about 80 for the water and air mixture at room temperature. That is to say, the effect of gravity on flow behavior in the former is considerably less than in the latter.

The flow rate of each fluid is adjusted by means of the flow-regulating valve. The experimental conditions are achieved by increasing or decreasing the water flow rate after determining the oil flow rate. The experiments are carried out in the range of superficial water velocity (J_w) of 0.0017 m/s to 0.7 m/s ($Re_w = 49 \sim 2.05 \times 10^4$) and superficial oil velocity (J_o) of 0.03 m/s to 0.4 m/s ($Re_o = 13 \sim 180$) and of void fraction (α) of 0.05 to 0.90, which is defined as the ratio of the water volume to the total volume.

3. Experimental Results and Discussion

3.1 Flow pattern

The observed flows are classified into seven basic patterns according to the flow behavior, as shown in Fig. 2. In the figure, hatching denotes the oil phase.

Table 1 Properties of fluids

Fluids	Viscosity (mPa·s)	Specific gravity	Surface tension (dyne/cm)
Water	0.894	1.0	71.95(Water-air)
Silicone oil	55.0	0.98	21(Silicone oil-air) 29(Silicone oil-water)

(a) Schematic diagram

(b) Details of oil-water mixing section

Fig. 1 Experimental apparatus

When the water flow rate increases under a constant oil flow rate, the flow pattern changes successively to bubbly, slug, and annular. Then, the continuous phase changes from oil to water and the flow pattern changes to inverted annular, inverted slug, or inverted bubbly flow where the water comes into contact with the pipe wall.

(a) Bubbly flow: The water droplets are distributed as discrete bubbles which flow in a continuous oil phase at the center of the tube.

(b) Slug flow I: Large bullet-shaped water slugs 40 mm to 200 mm in length and almost as wide as the diameter of the tube are separated by a continuous oil phase.

(c) Slug flow II (Semi-annular flow): Larger (0.3 ~ 1 m in length) bullet-shaped water slugs are seen, and the oil-water interface is rough and disturbed.

(d) Annular flow: Water flows at the center of the tube as a continuous core. Some water drops are sometimes contained in the oil film around the periphery of the tube.

(e) Inverted annular flow: Oil flows at the center of the tube as a continuous core and the water is in contact with the pipe wall.

(f) Inverted slug flow: Large bullet-shaped oil slugs flow in continuous water.

(g) Inverted bubbly flow: Discrete oil droplets flow in continuous water.

The flow shows a symmetrical shape in the cross section of the tube, as in a vertical tube, without being lifted upwards since the effect of gravity between the two phases diminishes due to their almost equal den-

sity. Here, since the interface between the water and oil slugs is disturbed and the thin oil slug is broken, the transition from semiannular to annular flow occurs. The oil film which flows around the periphery of the tube is thick with large waves. Then, as the water flow rate increases, a large oil droplet which separates from the oil film flows in the water core without being reentrained in the oil film. The water phase replaces the oil phase and the flow changes to an inverted flow where the water is in contact with the pipe wall. The oil droplets which are entrained from the oil film into the water phase in the core region are not reentrained on the oil film again because of both the low buoyancy force between the two phases and the almost equal inertial force between the water and oil.

3.2 Flow pattern map

The flow pattern map is shown against the superficial velocities of oil (J_o) and water (J_w) in Fig. 3. The Reynolds number based on each velocity is also shown on the respective axes. The thick hatched lines show such experimental transition lines. The broken lines and the parentheses, respectively, show the boundaries and the flow pattern of Charles et al.'s experimental results obtained using a mixture of mineral oil (viscosity of 65.8 c.p. and specific gravity of 0.98) and water as the working fluid⁽⁸⁾. Compared with Charles et al.'s results, the transitional slopes from bubbly and slug flows to inverted annular flow and between inverted flows are similar in spite of the different shape of the mixing section. In this experiment, the transition line from bubbly to slug flows is expressed by $J_o = 8.8J_w$.

Also, the experimental results are compared with the transition correlations in horizontal two-phase flows studied by Taitel and Dukler⁽¹³⁾ and Weisman et al.⁽¹⁴⁾, in Fig. 4. In the figure, the symbols denote the experimental results. The results calculated by substituting the physical properties of the respective liquids into Taitel and Dukler's⁽¹³⁾ and Weisman's correlations are shown by the respective lines. The agreement with Weisman et al.'s empirical correlation, shown by broken lines in the figure, is not very good, but that with Taitel and Dukler's semiempirical correlation is much better, as shown by solid lines, especially for the transition from bubbly to slug and from slug to annular flows.

3.3 Mean void fraction

The void fraction is defined as the volumetric fraction α of water to the tube volume. The measured mean void fraction is shown against the volumetric flow rate ratio β in Fig. 5. It is shown that the void fraction is increased and slip ratio s is also increased to about a value of 3 with an increase of J_w under a

Fig. 2 Flow patterns (◐ : oil phase)

Fig. 3 Flow pattern map (---: Charles et al.'s experimental results⁽⁸⁾)

Fig. 4 Comparison with Taitel and Dukler's⁽¹³⁾ and Weisman et al.'s⁽¹⁴⁾ correlations

Fig. 5 Void fraction

constant J_o . Here, the slip ratio s is defined as follows

$$s = \frac{J_w}{J_o} = \frac{J_w}{J_o} \cdot \frac{1-\alpha}{\alpha} \quad (1)$$

But as the flow becomes an inverted flow with the water film at the wall, the oil becomes faster than the water, and α is greater than β and s is less than unity. This transition to the inverted flow region occurs at the value of $\beta \approx 0.5$.

The experimental values of the mean void fraction are shown by symbols against the inverse Martinelli parameter $1/X$ in Fig. 6. In the figure, Lockhart

and Martinelli's⁽¹²⁾ and Wang's⁽¹⁰⁾ correlations and our recommended correlation of Eq. (2) based on all the experimental data are also shown.

$$\alpha = 1 - \left(1 + \frac{0.2}{X} + \frac{1}{X^2} \right)^{-8.0} \quad (2)$$

Next, the void fraction is correlated by the expression of the drift flux model as

$$\frac{J_w}{\alpha} = C_0(J_w + J_o) + U_{wj} \quad (3)$$

where C_0 is the distribution parameter and U_{wj} is the drift velocity. For each flow pattern, these values are given in Fig. 7. It is shown that the drift velocity U_{wj}

Fig. 6 Void fraction vs the inverse of the Martinelli parameter

Fig. 7 Correlation of the void fraction based on the drift flux model

is approximately equal to zero because of the almost equal-density fluids.

3.4 Pressure loss

The measured values of the pressure drop are shown in Fig. 8 against the ratio of superficial velocities J_w/J_o with the superficial oil velocity J_o as a parameter. Increasing the water velocity J_w under a constant J_o , the pressure loss increases according to the transition of the flow pattern, such as to bubbly, slug, and annular flows. When the flow pattern shifts to inverted annular and inverted slug flows with increasing J_w , the pressure loss decreases suddenly to a value of about one-eighth the initial value. That is to say, it is evident that the frictional resistance decreases greatly when water with a viscosity lower than that of oil flows along the tube wall as a liquid film.

A theoretical analysis of the pressure loss in annular and inverted annular flows has been made, assuming that both flows are laminar⁽⁷⁾. The results calculated are shown by solid and broken lines against the radius ratio r_i/r_o in Fig. 9. The vertical axis denotes the ratio of the pressure loss of the two-phase flow $\Delta P_{TP(Annular)}$ to that of the single-phase (liquid A) flow $\Delta P_{A(Full)}$. In the figure, the solid lines calculated by Eq. (4) correspond to the case where liquid A flows in the core region, and the broken line calculated by Eq. (5) corresponds to the case where liquid A flows along the pipe wall when liquid B is added to liquid A.

When liquid A flows in the core region, the ratio of the pressure loss is expressed as follows.

$$\frac{\Delta P_{TP(Annular)}}{\Delta P_{A(Full)}} = \left(\frac{r_o}{r_i}\right)^4 / \left[1 + 2 \cdot \frac{\mu_A}{\mu_B} \left\{ \left(\frac{r_o}{r_i}\right)^2 - 1 \right\}\right] \quad (4)$$

When liquid A flows along the pipe wall, the following is derived.

$$\frac{\Delta P_{TP(Annular)}}{\Delta P_{A(Full)}} = 1 / \left\{ 1 - \left(\frac{r_i}{r_o}\right)^2 \right\}^2 \quad (5)$$

It is shown that the value of $\Delta P_{TP(Annular)}/\Delta P_{A(Full)}$ for

Fig. 8 Pressure drop vs J_w/J_o

the solid line is less than unity, and depends on the values of the viscosity ratio μ_A/μ_B and the dimensionless radius ratio r_i/r_o . On the other hand, the broken line always shows a value greater than unity, independent of the value of μ_A/μ_B . In the figure, the experimental results of annular and inverted annular flows are plotted by the symbols $\circ$ and $\bullet$, respectively. It is shown that in annular flow, which corresponds to the broken line, the two results agree well. On the other hand, the symbol $\triangle$ shows the analytical results calculated by Wang et al.'s analytical method, which expresses the following interfacial friction factor⁽¹⁰⁾:

$$f_i = 0.005 \exp\left(-\frac{\delta}{2r_o}\right), \quad (6)$$

where δ is the film thickness and r_o is the inner radius of the pipe. Compared with the experimental results ($\bullet$), a more accurate estimation of the interfacial friction factor f_i may be desired.

Next, the pressure loss is correlated by the Lockhart-Martinelli method⁽¹²⁾, as shown in Fig. 10. The broken line denotes Wang et al.'s⁽¹⁰⁾ empirical equation and the solid line, Chisholm et al.'s⁽¹²⁾ correlation. Except in the inverted regions, the experimental results show values 50 percent larger than those obtained using Wang et al.'s equation. On the other hand, in the inverted region, where the water is in contact with the pipe wall, most values are under unity, as shown by the filled marks ($\bullet$). Hence it is clear that they cannot be estimated using the former correlations in the inverted flow region.

Fig. 9 Pressure loss ratio

Here, an analytical correlation, which was made by Brauner⁽¹⁵⁾ for the region of annular flow, will be applied by partly modifying the interfacial frictional coefficient f_i .

$$\tau_i = f_i \cdot \rho_c (U_c - U_w)^2 / 2 \quad (7)$$

$$f_i = B \cdot C_c \{ D_c (U_c - k U_w) / \nu_c \}^{-N_c}, \quad (8)$$

where τ_i is the interfacial shear stress, ρ is the density, U is the mean velocity, ν is the dynamic viscosity, B is the augmentation of the interfacial shear, k is a modification factor, and the subscripts c and w denote the regions of core and pipe wall, respectively. The

following dimensionless equation (9) is derived by substituting Eq. (7) into the momentum equation of each phase.

$$\frac{\rho_c}{\rho_a} \left(\frac{\nu_a}{\nu_c} \tilde{D}_c \tilde{U}_c \right)^{-N_c} \left(1 - \frac{k}{\phi} \frac{\tilde{U}_w}{\tilde{U}_c} \right)^{2-N_c} \left(\frac{1}{\tilde{A}_w} + \frac{1}{\tilde{A}_c} \right) \tilde{S}_i \tilde{U}_c^2 - \frac{\rho_w}{\rho_b} X^2 \left(\frac{\nu_b}{\nu_w} \tilde{D}_w \tilde{U}_w \right)^{-N_w} \frac{\tilde{S}_w}{\tilde{A}_w} \tilde{U}_w^2 = 0 \quad (9)$$

$$\text{Here, } X^2 = \left(\frac{4 C_w}{D} \right) \left(\frac{U_{bs} D}{\nu_b} \right)^{-N_w} \cdot \frac{\rho_b U_{bs}^2}{2} / \left[B \left(\frac{4 C_c}{D} \right) \left(\frac{U_{ac} D}{\nu_a} \right)^{-N_c} \frac{\rho_a U_{as}^2}{2} \right],$$

Fig. 10 Comparison of the experimental results with the Lockhart-Martinelli⁽¹²⁾ correlation and Wang et al.'s⁽¹⁰⁾ experimental expression

Fig. 11 Comparison of the experimental results with those calculated using Eq. (9)

$\phi = \frac{U_{as}}{U_{bs}}$, A is the cross-sectional area and the tilde ($\sim$) denotes a dimensionless value. The calculated results are shown against X in Fig. 11 compared with the experimental results. In the figure, the solid lines express the case calculated for $B=1$ and the broken lines denote the case of $B=10$ for both $J_o=0.04$ and 0.2 m/s. It is shown that the two agree well in the inverted flow region.

4. Conclusions

For the purpose of simulating experiments on two-phase flow under a microgravity environment on earth, experiments on an almost equal-density liquid-liquid two-phase flow were carried out. As a result, it was found that the effect of gravity between the two phases can be simulated, but that a difference in inertia between the two phases occurs. The results are summarized as follows.

(1) The flow patterns observed in the experiments are classified into seven basic types.

(2) The mean void fractions are correlated by the drift flux model for their respective flow regimes.

(3) In the flow pattern observed when the oil is in contact with the pipe wall, the measured pressure loss agrees with the Lockhart-Martinelli correlation. In the inverted flow pattern observed when the water is in contact with the pipe wall, the pressure loss differs greatly from the Lockhart-Martinelli correlation. The modification of Brauner's analytical result agrees well with the experimental results in the inverted flow region.

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