2001ESASP.454...63X

INVESTIGATION ON TWO-PHASE FLOW REGIMES IN MICROGRAVITY

J.C. Xie, H. Lin, J. F. Zhao, W. R. Hu
National Microgravity Laboratory/CAS; Institute of Mechanics, Beijing 100080, China
Tel: 86-10-62615538, Fax: 86-10-62561284, E-mail: jcxie@imech.ac.cn

A.V. Ivanov, A.Yu. Belayev
Keldysh Reseach Center, 125438, Moscow, Onezhskaya, 8/10, Russia
Tel: 007-095-4564608, Fax: 007-095-4568228, E-mail: kerc@elner.msk.ru

Abstract: The experiment of carbogal-air two-phase flow was conducted on board the "Mir" Space Station in August last year. Two-phase flow regimes were investigated to study the flow pattern transitional features depended on the superficial velocity ratio of gas to liquid. The test tube was 356mm in the length with 10 mm inner diameter. Bubble flow, slug flow, annular flow and the transitional flow from slug to annular were observed to exit. A remarkable annular flow region at very liquid flow rate exists in the flow pattern map. The experiment results obtained in the microgravity condition of 10^{-5}g are presented. Some data taken under different g-level are also given, as an example, in this paper.

INTRODUCTION

Studies of gas-liquid two-phase flow have been conducted for many years by the unclear and petroleum industries. The influence of gravity on gas-liquid flows has been demonstrated by the ground-based experiment. Gas-liquid flows in reduced gravity have many applications in space, such as cryogenic transfer and storage, active two-phase transport and control system, condensation and flow boiling process, design and operation of life supporting system, and so on [1]. Many studies have been also conducted to investigate characteristics of two-phase flows in microgravity conditions, and efforts have been made to develop the flow pattern map and the transition criteria [2-10]. The early studies of the two-phase flow in the reduced gravity conditions have been reviewed by Rezkallah [11]. Recent reviews on the experimental and the theoretical efforts of the two-phase flow studies in the reduced gravity have been given by Hewitt [12].

Under normal gravity, buoyancy plays a dominant role in controlling the behavior of two-phase system. In microgravity environment, the characteristics of two-phase flow are quite different, because of the greater impact of surface tension forces in the slower flows and the lack of stratification caused by the reduced influences of buoyancy forces. The typical flow patterns have been classified such as the bubble flow, the slug flow, the slug-annular transition flow and the annular flow in microgravity conditions. It is believed that the classification of the two-phase flow pattern depends on the fluid flux, the content of gas, and liquid physical properties. However, most of the experimental investigation have been conducted in the reduced gravity conditions using either the free fall in drop tower facilities in a short microgravity period of several seconds or the parabolic flights of aircraft in a low gravity. The limited test period associated with the method makes it difficult to eliminate the transient effect of the rapid change in gravitational fields. The influence of residual gravity seems also to be further studied. For this reason, the investigation on the flow regimes under long, steady microgravity conditions with high μ–g level is helpful to make better understanding of the characteristics of the two-phase flows.

The experiment of air-carbogal two-phase flow regimes depended on the superficial velocities of the gas and liquid phases were conducted on board the "Mir" Space Station. In this paper, the two-phase flow pattern data taken microgravity condition of $10^{-5}g_0$ are presented. Transitions between different flow patterns are discussed. The experiment data are also compared with that taken by others during parabolic flight. Several flow patterns observed at approximately the same flow rate under different gravity conditions, as an example, are also presented.

EXPERIMENTAL APPARATUS

The experimental facility is composed of the organic glass test section, the pneumohydraulic system and the measuring and recording equipment, as shown schematically in figure 1. The test section is 35.6 cm long and has a 16x16 mm^2 square cross-section with a 1cm-diameter bore along the axis. There is a mixer at the inlet of the test tube, which is designed as a Venturi tube with three groups of 0.75 mm diameter drillings distributed uniformly at different cross section around the periphery of the Ventury tube. The flow patterns in a part of 15 mm long near the outlet of the test tube were observed and recorded. A closed loop system operated with a certain volume of the gas and the liquid. Carbogal liquid and air were used as the liquid phase and the gas phase, respectively. Before the execution of the experiment, a part of the air was first compressed from the station compartment into the system. The air was charged in a receiver up to a pressure of 1.0 MPa. The carbogal liquid was stored in a liquid vessel. When the facility operated, the two phases were supplied into the test section through the mixer. After the gas-liquid flow passed through the test tube, the mixed two-phase flow entered a phase separator, where the liquid remained in it and the air was separated and stored in an elastic rubber vessel. When the separator is totally filled with the liquid or the pressure in receiver decreased to a specific value of 0.15 MPa, the liquid was pumped from the phase separator to the liquid vessel and the air was compressed to the air receiver from the elastic vessel for further experiments. The liquid flow rates were measured by two turbine flowmeters for different normal flow ranges of 20~100 cm^3/s and 30~160cm^3/s, respectively. Both of the two flowmeters have linear characteristics and a measuring error of ±1.0 % within the full span. Two manometers indicated the pressure in the receiver and the pressure after the pressure regulator, respectively. The air flow rate averaged over the measurement time was determined through the receiver pressure drop according to the ideal gas state equation. The calibrations conducted on the ground show that the absolute air pressure in the test section equals nearly the atmospheric pressure when the rubber vessel is not full and the temperature changes in the receiver can be neglected for determining the air amount used. In general, the uncertainties are estimated to be less than 10% over the measuring range of liquid and gas superficial velocities.

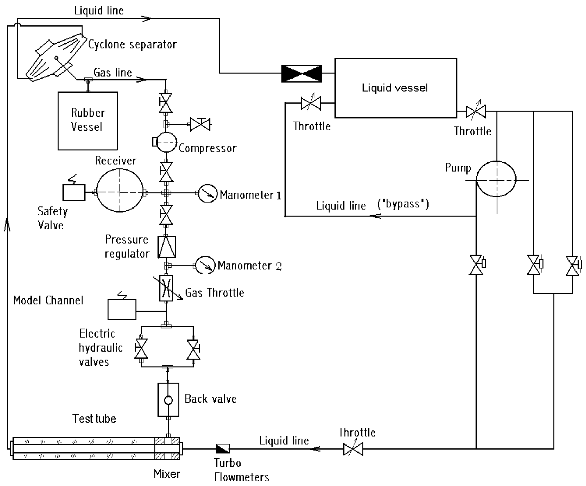


Fig. 1. Schematic diagram of the experimental facility.

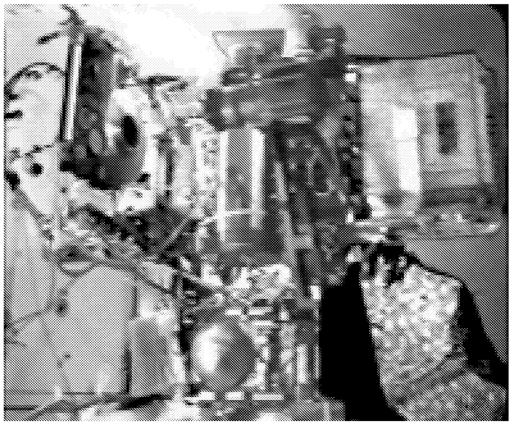


Fig. 2. The experiment facility mounted on the rotation stand aboard "Mir" Space Station.

The flow patterns and the information of gas and liquid flow rate were recorded by the digital video camera SONY DCR-VX1000. In the space experiment, the camera operation mode was set as the automatic mode (50 fps, automatic exposure and sharpness), due to the misoperation. So, the video recording was conducted in a relatively low shutter speed, instead of 1/2000 second as designed, which results in the image blur to some extend. The experimental facility was mounted on a stand used as a centrifuge. Rotating the stand with the corresponding angular velocities can provide different g-loads. The picture of the experimental facility with the stand used on board the "Mir" space station is shown in figure 2.

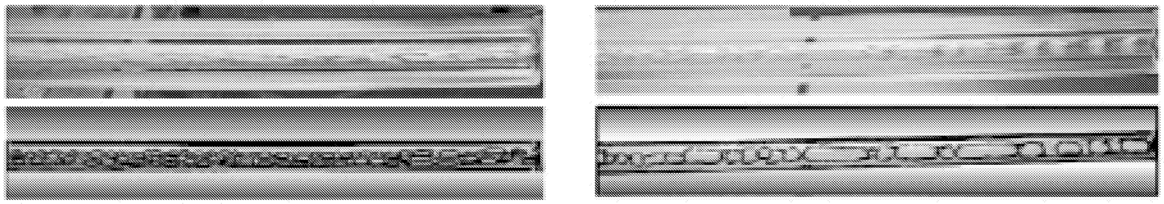
Table 1. physical properties of carbogal liquid and water (20°C)

property / liquid	Density ρ (Kg/m^3)	Viscosity ν (m^2/s)	Surface tension σ (N/m)
carbogal	1858	1.05×10^{-6}	0.019
water	1170	1.006×10^{-6}	0.072

Carbogal liquid is odorless, colorless, non-toxic, and can well wet with the inner wall of the organic glass (the contact angle is within $\theta = 0° \sim 7°$). Other main physical properties of carbodal liquid, together with that of water, are summarized in table 1.

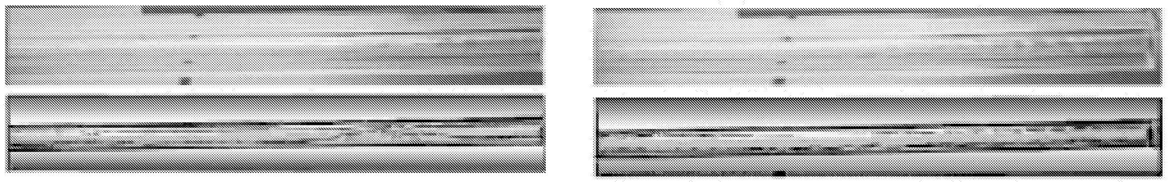
FLOW PATTERN OBSERVATIONS

The flow pattern was observed at different ratios of gas-liquid superficial velocities in the microgravity environment of $10^{-5}g_0$, which is the background microgravity level of "Mir" space station. The gas superficial velocities ranged from 0.09 to 6.29 m/s, while the liquid phase velocity ranged from 0.001 to 0.808 m/s. Bubble flow, slug flow, annular flow and the transition flow from slug to annular were observed to exist. The bubble flow is featured by the presence of gas bubbles whose diameter is smaller or much smaller than that of the test tube, such as in figure 3 (a). When the superficial liquid velocity increased to about 0.8 m/s, the relative bubbles in the bubble flow were broken to very small bubbles, forming the finely dispersed bubble flow. The slug flow is recognized when the so-called Taylor bubbles exist in the flow. In this case, the bubble diameter is close to tube diameter or the length of the elongated gas bubble is greater than the tube diameter with the liquid slugs between the Taylor bubbles, see figure 3(b). Only two slug flow patterns were identified in the present experiment. The transitional flow (slug-annular flow) is the transition between slug and the well developed annular flows. In that case, the liquid flows in a form of film at the tube wall, and gas flowed in the center forming long gas bubbles which generally have no regular hemispherical nose and rear shapes, as seen in figure 3 (c). The details of the slug-annular flow cannot be distinguished clearly from the videotape. When the liquid flows at the tube wall and the gas phase flows uninterruptedly at the center of the tube, the annular flow, figure 3(d), is observed. The flow pattern observations is plotted in terms of the superficial velocities in figure 4. As can be seen, a particular annular region where the annular flow appears at very small liquid flow rate features the flow pattern map. To make comparison, the data, together with that from Zhao & Rezcallah (1993, 1995) [3, 4], are plotted in figure 5. If the slug flow pattern is grouped with the bubble low pattern, the flow patterns in this map are divided into three main regions: bubble and slug flow region, slug-annular transitional flow region (the intermediate region), and the annular flow region. Compared with the experimental data obtained during parabolic flight, it can be seen that the annular flow and the transitional flow appear at lower gas flow rate in general. In addition to other factors, this may be partially due to different liquid-gas phases with different surface tension were used in these experiments. The surface tension for carbogal liquid and water are σ=0.019 N/m and σ=0.072N/m, respectively. Hence, according to the force analysis and the definition of gas weber number, relative lower inertial force is needed to balance the surface tension



(a) Bubble Flow
(V_{SL}=0.16 m/sec, V_{SG}=0.09m/sec)

(b) Slug Flow
(V_{SL}=0.06 m/sec, V_{SG}=0.09m/sec)



(c) Slug-Annular Flow
(V_{SL}=0.0.05 m/sec, V_{SG}=2.10m/sec)

(d) Annular Flow
(V_{SL}=0.16 m/sec, V_{SG}=0.09m/sec)

Fig. 3. Typical two-phase flow patterns observed in the experiment on board the "Mir" space station.

force. That is, the gas superficial velocity should be relatively low when the transitions take place. However, if the slug flow is also regarded as the transitional flow from bubble to annular and grouped into the intermediate region, it is found that the transition from the bubble flow to the transitional flow occurs at the similar range of gas flow rate and the transition line has a upward positive slope for both the two data sets. That shows the transition begins at lower gas flow rate for the lower liquid flow rate. Figure 5 also shows that the transitional flow region covers a wide range of liquid and gas flow rate. It implies that the transition from slug flow to annular flow is slow and gradual process.

The flow pattern map shows that the remarkable annular pattern region appears at very low liquid velocities (U_{SL}<0.015m/s) and at relatively high gas velocity. It can be observed from the videotape that the liquid film of the annular flow is quite smooth with wave crests on it. The wave crest move in a spiral due to the different velocities of the two phases in the flow. In this case, the liquid flow rates are lower than the flowmeter's sensitivity threshold. So the liquid velocities were evaluated basing on the analysis of the roll wave propagation velocity in the liquid film. The recent investigations have shown that the liquid velocity of a film flow in a tube is equal to about half of the roll wave propagation velocity in the liquid film. As mentioned above, carbogal liquid can wet well the test tube wall. The annular flow patterns appeared at very low liquid flow rate is supposed to be partially attributed to the good wettibility and high μ-g level conditions.

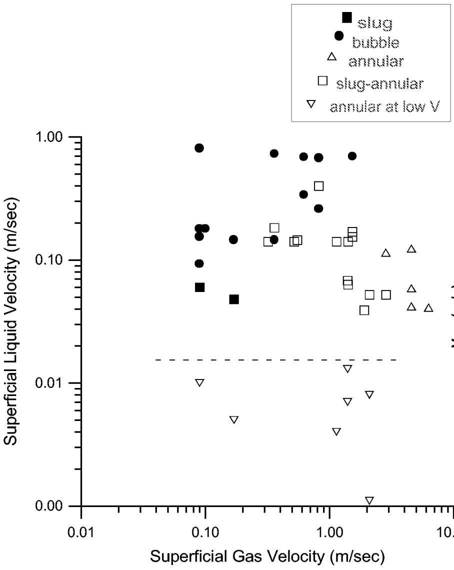


Fig. 4. Carbogal-air two-phase flow data taken aboard "Mir" space station.

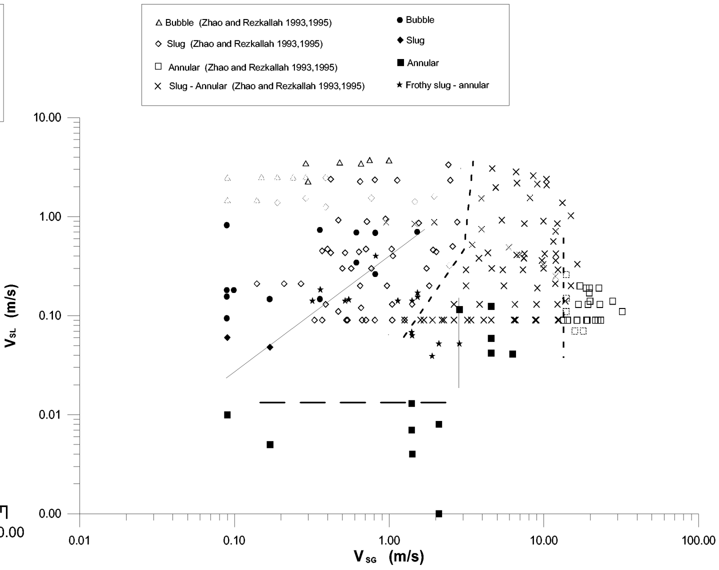


Fig. 5. Comparison of microgravity flow pattern with water-air data of Zhao & Rezcallah (1993, 1995).

The length-to-diameter ratio L/D is an important parameter, which influences the collision of small bubbles, and the bubble size. The ratio is L/D≈36 for the present experiment. If the influence of the test tube entrance is taken into account [12], the two-phase flow is perhaps still in developing with the relative small tube length for the small flow rate. That would influence the definition of the transition line from the bubble and slug flow region to the intermediate flow region. But for the relatively high gas flow rate, the developing length would be much smaller [7]. Our ground -based experiment on the ground analog has demonstrated that the length within which the flow pattern becomes stable doesn't exceed 15~18 cm at the maximum flow rate (700cm^3/s for air, 75cm^3/s for liquid) supplied in the present experiment with the same test tube. Therefore, the flow pattern in the higher gas flow rate region (intermediate and annular regions) of the flow pattern map should be referred to the well-developed ones.

In addition to other factors, the influence of residual gravity on the two-phase flow regimes seems need to be studied further, especially when the liquid or the gas flow rates are very low. The notable residual gravity may cause phase slip and influence the flow pattern. High μg-level is advantageous to the coalescence of small bubbles, increasing the collision rate and forming larger bubbles. If Eotvos number,

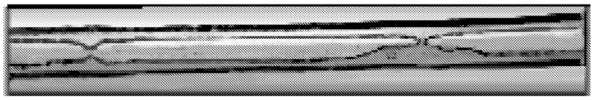
2001ESASP.454...63X

Eo, is used to describe influence of residual gravity, the Eo is 0.0095 for the present case, while Eo=0.25 for the experiment of Zhao & Rezcallah (1993, 1995) conducted during parabolic flight. The difference of μ-g level may give rise to the discrepancy of experimental data obtained in different experiments.

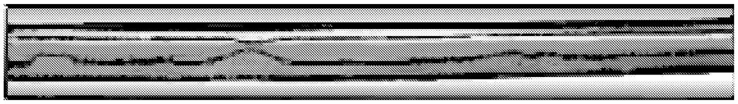
The two-phase flow patterns observed at approximately the same gas and liquid flow velocity but in different g-levels are given, as an example, in figure 6. It can be seen that the different g-level effects the flow pattern apparently. Phases slip still can be observed when the g-load decreases to $0.014g_0$.

Superficial Gas Velocity - approx. 0.06 m/sec

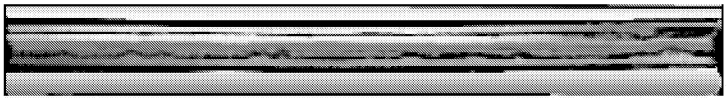
Superficial Liquid Velocity - approx. 2m/sec



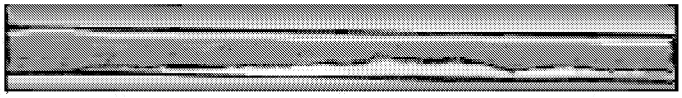
$g/g_0 = 0.00001$ Slug-annular flow



$g/g_0=0.014$ Transition between annular and slug flows



$g/g_0=0.1$ Transition between annular and wavy flows



$g/g_0=1$ Wavy flow

Fig. 6. Two-phase flow patterns observed in different g-levels.

CONCLUSIONS AND DISCUSSION

The experiment of carbogal-air two-phase flow was conducted on board the "Mir" space station in a long and steady high μ-g environment of 10^{-5}g for the first time. Bubble flow, slug flow, slug-annular transitional flow and annular flow has been observed to exist.

The transitional flow region covers a wide range of gas and liquid superficial rates, which can also be seen from the data taken on low gravity aircraft. That means the transition from slug flow to the annular flow is a gradual process.

A new annular flow region with very low liquid flow rate was observed, which features the flow pattern map. It is understandable when considering the liquid's behavior that a certain volume of liquid with good wettability tends to attach to the surface of a container's inner wall in microgravity conditions.

The transition from bubble and slug flow to the slug-annular transitional flow, and from the transitional flow to annular flow take place at relatively low gas flow rate, compared with the transitions for the air-water flows obtained on low gravity aircraft. It is partially attributed to that carbogal liquid and water have different surface tension. Besides, the steady and high μ-g level may also contribute to the forming of the patterns and their transitions, especially when the flow rate of gas or liquid is low. In addition, the good wetting of carborgal liquid with the test tube wall maybe effect the forming of flow pattern to some extend. Further experiment is under preparing to make a better understanding of it.

It is be noticed that the relative small length-to-diameter ratio of the test tube perhaps result in the two-phase flow not full developed for small gas flow rate. However, for the relative high gas flow rate, the flow configuration observed in the present experiment should be well developed [7, 12]. Our ground-based experiment results also support this view.

The relatively long exposure of the video recording causes the image blur to some extends, and that perhaps result in some discrepancy in defining the flow patterns.

ACKNOWLEDGMENTS: The project is partly supported by the National Natural Science Foundation (19789201) of China.

REFERENCES

1. Swanson, Theodore D., Juhasz, Al, Long, W.Russ, and Ottenstein, Laura, Workshop on Two-phase Flow Behavior in a Space Environment, NASA Conference Publication 3043, 1989
2. Dulker, A.E., Fabre, J.A., McQuillen J.B., Vernon, R., Gas-liquid Flow at Microgravity Conditions: Flow Patterns and Their Transitions, Int. J. Multiphase Flow, 14, 4, (1988) 389.
3. Zhao L., Rezkallah K. S., Gas-Liquid Flow Patterns at Microgravity Conditions, Int. J. Multiphase Flow, 19, 5, (1993) 751.
4. Zhao L., Rezkallah K. S., Presure Drop in Gas-Liquid Flow at Microgravity Conditions, Int. J. Multiphase Flow, 21, 5, (1995) 837.
5. Rezkallah K. S., Weber Number Based Flow-Pattern Maps for Liquid-Gas Flows at Microgravity, Int J. Multiphase Flow, 22, 6, (1996) 1265.
6. Colin, C., Fabre, J., McQuillen, J., Bubble and Slug Flow at Microgravity Conditions, Chem. Engng. Comm., 141-142, (1996) 155.
7. Zhao, J.F., Hu, W.R., Slug to Annular Flow Transition of Microgravity Two Phase Flow, Int. J. Multiphase Flow, 26, 8 (2000) 1295.
8. Wölk, G., Dreyer, M., Rath, H.J., Two-Phase Flow in Small Diameter Channels under Low and Normal Gravity, Drop Tower Days 1998-in Hokkaido (extended abstracts).
9. Bousman, W.S,, Mcquillen, J.B., Witte, L. C., Gas-Liquid Flow Patterns in Microgravity: Effects of Tube diameter, Liquid Viscosity and Surface Tension, Int. J. Multiphase Flow, 22, 6, (1996) 1035.
10. Rezkallah, K.S., A Comparison of Existing Flow-Pattern Predictions During Forced-Convective Two-Phase Flow under Microgravity Conditions, Int. J. Multiphase Flow, 16, 2, (1990) 243.
11. Hewitt, G.F., Multiphase flow, The Gravity of the Situation. 3rd Microgravity Fluid Physics Conf., NASA CP-3338, p.3 (1996).
12. Lee, J., Scaling Analysis of Two-Phase Gas-Liquid Flow Pattern in Microgravity, 31st Aerospace Sciences Meeting & Exhibit, January, 11-14, 1993. Reno, NV.