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PROCEEDINGS OF THE SECOND INTERNATIONAL SYMPOSIUM ON MULTIPHASE, NON-NEWTONIAN AND REACTING FLOWS (ISMNRF'04)

Edited by ZHOU, Lixing

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September 10-12, Hangzhou, China

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PREFACE

The Second International Symposium on Multiphase, Non-Newtonian and Reacting Flows will be held jointly with the Fourth International Symposium on Measurement Techniques for Multiphase Flows in Hangzhou, China in the time period of September 10 to 12, 2004. On behalf of the International Scientific Committee and the Local Organizing Committee we would like to welcome all the delegates to participate in the symposium.

The First International Symposium on Multiphase, Non-Newtonian and Physico-Chemical Flows, organized by the Chinese Society of Theoretical and Applied Mechanics and other Chinese societies, was successfully held in Beijing in October, 1997. The most distinguished scientists from the United States, Great Britain, Japan, China, Australia and other countries organized and attended this meeting. That symposium brought together both international experts and Chinese experts in the related fields to exchange information of common interest. Since then, seven years have passed, and recently, the scientists in these fields both in the world and in China suggested organizing the Second International Symposium on Multiphase, Non-Newtonian and Reacting Flows to continue their discussion on the state-of-art, advances, new ideas and future research needs.

The papers in this volume cover fundamental studies, numerical models, measurements and application of multiphase and non-Newtonian flows. This volume contains totally 100 papers, including 8 invited papers, 19 papers of gas-solid flows, 9 papers of liquid-solid flows, 6 papers of reacting flows, 31 papers of gas-liquid flows, 5 papers of liquid-liquid flows, 12 papers of non-Newtonian flows and 10 papers of flows in porous media. These papers are selected from 126 submitted manuscripts. The acceptance of these papers is based on the reviewer's comments by the members of the Scientific Program Committee, and finally on the decision made in the meeting of the Scientific Program Committee.

Thanks to all invited speakers and authors of oral presentations, they made much contribution to this symposium. We appreciate very much the paper review work done by the members of the Scientific Program Committee and the administrative organizing work for preparation of this symposium done by the Local Organizing Committee.

Special thanks should be given to the National Natural Science Foundation of China for providing us the financial support

Finally, thanks should be given to the Secretary General Ms. Wei Wang. and the Secretary Dr, Liyuan Hu for their organizing work and help in editing the manuscripts of this volume.

Best wishes to all participants for enjoying a fruitful symposium in the golden autumn season in the city of beautiful West Lake (Xihu), Hangzhou, China.

Lixing Zhou
Tsinghua University
July 26, 2004

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5. Gas-Liquid and Liquid-Liquid Flows

The Second International Symposium on Multiphase, Non-Newtonian and Reacting Flows'04, September 10 -12, 2004, Hangzhou, China

DEVELOPMENTS IN TURBULENCE MODULATION IN DISPERSED TWO-PHASE FLOWS

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EXTENDED ABSTRACT

The turbulence in the carrier, or continuous, phase of a dispersed phase flow plays a significant role in the dynamics of the flow, the heat and mass transfer (mixing) and the particle/droplet dispersion. Previous studies have shown that large particles appear to enhance carrier phase turbulence while small particles seem to attenuate the turbulence. The reasons for these trends and not fully understood but probably are attributable to wakes generated by the particles and damping by the particle surfaces.

Several models for particle generated turbulence have appeared in the literature. Some models are empirically based, others are based on point models and still others are based on averaged models. Also there has been a significant recent effort using direct numerical simulations. Some models treat the averaged equations as if they represent the conditions at a point and develop equations for turbulence in the same manner as for single-phase flows. This approach, though very common, leads to a serious fallacy.

One approach to developing multiphase flow turbulence equations is start with the mechanical energy equation. By averaging this equation, an expression for the turbulence energy ensues with the correct physics. The equation shows that the turbulence energy production derives from velocity gradients in the flow, diffusion of turbulence energy, the generation due to particle drag, the conversion from particle kinetic energy to carrier phase energy and the dissipation due to viscous effects. This equation reduces to the correct form for the simple, idealized case of particles rigidly suspended in a flow.

With experiments for turbulence generation in quiescent flows, there is no generation by velocity gradients and the diffusion and conversion are minimized so the generation of turbulence is equal to the dissipation. Expressing the dissipation in terms of the Taylor microscale yields an equation for the ratio of the microscale to the particle size. Reduction of data for quiescent flow experiments shows that the length scale ratio correlates with the particle Reynolds number.

Studies of turbulence generation in gas-particle flow behind a grid show that the turbulence length scale depends on the particle volume concentration. Obviously, the length must reduce to the single flow values as the particle volume fraction approaches zero. Some of the data also suggest that the length scale approaches an asymptotic value as the volume fraction increases. This observation suggests that there is a point where the wakes from the particles constitute the entire flow. This is referred to as the saturated condition.

For flows near boundaries, the primary turbulence generation term is the velocity gradient. If the ratio of the particle-generation term to the velocity-gradient generation term is small, the particles likely do not enhance turbulence. This trend has been observed in channel flows.

In jets flows, turbulence production is balanced by convection. On comparing water jets and air jets, the turbulence generated by particles is significantly larger for water jets than air jets. Thus the influence of particles on turbulence is larger in water jets, which have been borne out by experiment.

Direct numerical simulations are playing a more significant role in turbulence modeling and the results are yielding useful information. It is important that the effect of the particle surface be included to have a meaningful simulation.

There is still considerable effort needed to understand turbulence modification by particles. Also there is a need to develop reliable models for practical LES simulations.

The Second International Symposium on Multiphase, Non-Newtonian and Reacting Flows'04, September 10 -12, 2004, Hangzhou, China

MULTIPHASE FLOW IN MICRO-CHANNELS

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ABSTRACT

This report summarizes the experimental works on gas-liquid two-phase flow in micro channels recently carried out by the present author and his co-workers. Two-phase flows are visualized with a microscope and a high speed video camera for air-water flow in circular tubes of 20, 25, 40, 80 and 100 μm in inner diameter. Several distinct flow patterns including newly found flow patterns are identified. Based on these observations, two-phase flow pattern transition boundaries are constructed in a flow pattern map. The cross sectional average void fraction was also measured from high speed video images frame by frame. The results are well correlated by an empirical correlation of $\alpha = 0.9\beta$. Finally, a visualization technique adopting proton radiography is mentioned for its application to opaque liquid-gas two-phase flows and two-phase flows in opaque micro-channels.

Keywords: gas-liquid two-phase flow, micro-channel, flow patterns, void fraction, proton radiography.

INTRODUCTION

Two-phase flow in micro channels attracts people's concern in its wide applicability to modern and advanced science and technologies in micro fluid devices, such as MEMS (micro electro-mechanical systems), electronic cooling, micro heat exchangers, micro chemical reactors, nuclear transfer derived from somatic cells, blood flows in blood tubes and so on. Figure 1 shows an example of recent design of multi-chip module using 110 micro-channels for electronic cooling (Ishizuka, [1]). A typical channel geometry is a 57 μm width x 180 μm depth x 11 mm long square duct. The micro-channel heat exchanger is thus the most typical application.

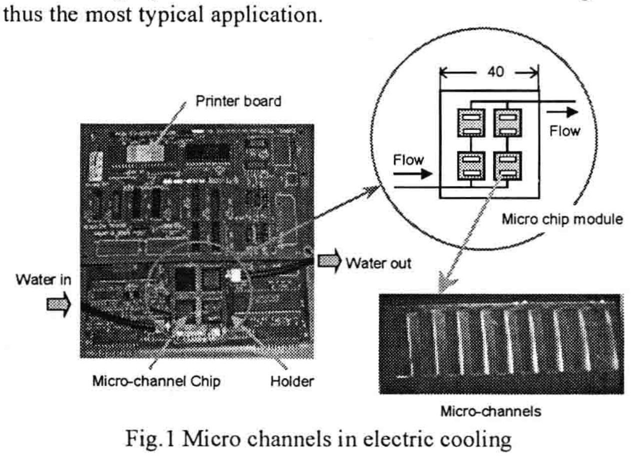

Fig.1 Micro channels in electric cooling

Another example can be seen in ink jet printing technology. Figure 2 shows the principle of a bubble jet printing with a heating element which works as an actuator creating an impulsive pressure for droplet ejection. When a current is applied to the heating element installed in the nozzle in a very short time, the temperature of the liquid ink adjacent to the heater rises very rapidly to generate a vapor bubble. The pressure inside the bubble reaches to several tens bars which is large enough to push the liquid ink as a droplet (Asai et al., [2]).

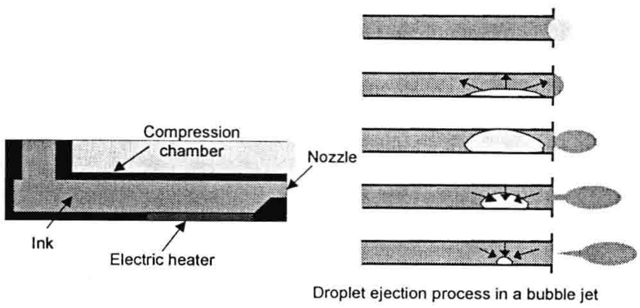

Fig.2 Bubble jet printing

A blood flow in blood tubes with diameter smaller than about 100 μm is also an example of multiphase flow in micro-channel. The blood flow is a mixture of red and white blood cells suspended in plasma, causing big flow resistance in micro blood tubes of such small diameters, which imposes an enormous stress on the human heart. The mechanism of this increase in flow resistance due to white blood cells is however not made clear yet (Seki, [3]).

The recent developments in the MEMS fabrication technology have definitely widen the application of miniature thermal and mechanical systems in various fields, and fabrication of very small channels of the order of even 1 μm has thus become possible. In such small tubes, surface forces rather than body forces dominate flow and heat transfer phenomena, and the interactions between the fluid and the walls become therefore very important. In other words, surface tension and viscous forces dominate over gravitational force. The inertia forces are also important. This means, in a practical sense, that a very big pumping power is needed to circulate the flow in such small micro tubes due to viscous pressure drop. For example, a capillary sequencer of about 50μm diameter glass tubes which is often used in genome analyses needs a few MPa high pressure pump to circulate the polymer fluid. Flow instability due to the compressibility of the gas involved in the entrance section and supply lines connected to the test tube is another problem. Furthermore, sub-micron tubes may change the physical properties of fluids such as viscosity, ice point and etc due to molecular and electro kinetic forces.

In general, performance characteristics of gas-liquid two-phase thermal-hydraulics in practical engineering devices with conventional length scales are generally expressed in non-dimensional forms of equation, and we have thus more or less well defined similarity laws based on experiment or theory. However, there is a severe lack in our current understanding as to the application limits within which the concept of characteristic length scales included in these similarity laws can be successfully applied in the smallest channel. In micro-channel flows, the surface forces rather than body force dominate the flow and heat transfer performances, and dynamic and static interactions between the fluid and the walls become therefore very important. Namely, the surface tension and viscous forces as well as inertia forces dominate over the gravitational force. Two-phase flow characteristics in micro-channel flows are thus supposed significantly to change from those observed in channel flows with conventional scales.

The classification of flow channels is given as follows by Kandlikar and Grand [4].

Conventional channels:	$D_h > 3mm$
Minichannels:	$3mm \geq D_h > 200\mu m$
Microchannels:	$200\mu m \geq D_h > 10\mu m$
Transitional channels:	$10\mu m \geq D_h > 0.1\mu m$
Molecular nanochannels:	$0.1\mu m \geq D_h$

These classifications were proposed originally for single phase gas flows based on the Knudsen number at near atmospheric pressure by taking into account the mean free path. Although the gas-liquid two-phase flow is not as simple as single-phase flow in its multi-scale structured flow with various time- and spatial-scales and deformable interfaces, they recommended the above classification for two-phase flow as well. Based on our experiences in two-phase flow observation [5~11], the above classification for two-phase flow as well. Based on our experiences in two-phase flow observation [5~11], the above classification reflects fairly well the experimental results for air-water two-phase flow over the pressure range from 1~5 atmospheric pressure. Our feeling is, however, that the two-phase flow behavior drastically changes for channel diameters smaller than 100μm. In this study, we therefore restrict ourselves to gas-liquid two-phase flows in channels with diameter smaller than about 100μm.

We will report the results of our visual observation of two-phase flow patterns prevailing in such small channels as 100, 80, 40, 25 and 20 microns in diameter. We also measured the cross sectional average void fraction frame by frame of the video images taken by a high speed video camera.

Finally, an advanced visualization technology applicable to multiphase flow in opaque micro or mini channels or opaque liquid-gas two-phase flow in micro-channels will be mentioned. This technique adopts a proton radiography using a proton beam accelerated by an accelerator. Since the proton is a charged particle, its path is easily controlled by electro magnetic fields. Because of this, a uniform and high beam flux is obtained which results in very sharp and clear images that cannot be obtained by conventional neutron radiography. This technique was successfully developed and applied to visualize very complex natural circulation of vapor-liquid flow in a miniature serpentine heat pipe by one of the present author's colleague (Takahashi [12,13]).

EXPERIMENTAL SETUP AND PROCEDURES

A schematic diagram of the test facility for air-water experiment is shown in Fig.3. We used as working fluids commercially sold purified water for chromatography and filtered air supplied from a high-pressure gas bottle. The test section consists of a transparent silica or quartz capillary tube with circular cross-section positioned horizontally. The tube inner diameters we tested are 20, 25, 40, 80 and 100μm. The whole length of the test tube ranges from 10 to 16 mm, depending on the different designs of the mixing zone leading to the test section. From our experience, we know that two-phase flow pattern in micro-channels generally tends to alternate with time from one flow pattern to another. Use of a pneumatic pump for liquid circulation is therefore preferably needed to minimize the effects of flow pulsation and contamination due to mechanical pumps.

Prior to experimental runs, the test section was cleaned either by drawing ethanol through the test section or by being treated with the combination of mechanical cleaning with a soft brush and ultrasonic vibration in a pool of high purity distilled water, ethanol, and dilute hydrochloride acid solution.

Optimal designs of the mixing section and the connecting lines are also required to establish stable two-phase flows in micro-channel experiments, since high-pressure gas injection into the test section which compensates a large pressure drop in the micro-channel incorporates the effect of compression and expansion of the gas phase both in the connecting lines and in the mixing section. These may lead to a flow pulsation. We therefore paid attention to the design of the mixing section and connecting lines. The 1/4" or 1/16" diameter stainless steel tubes are used for the main connecting lines to avoid the effect of possible piping inflation. Figure 4 shows typical examples of the mixing section designs we used in our experiment. In order to attain stable two-phase flow, the liquid may naturally form a converging nozzle.

The uniformity of the micro-channel dimensions in the axial and radial directions is of importance. An irregular or rough surface may result in a change of two-phase flow patterns and friction loss, while a non-uniform distribution in diameter along channel axis may cause flow pulsation. The former is, in general, the case with metallic tubes, and the latter with plastic or glass tubes. We examined the uniformity of the micro-channels by using a laser microscope. Figure 5 shows enlarged cross sectional pictures of typical micro-channels we tested (Suzuki [11]). We confirmed that the micro-channels we tested in the present work are in uniform dimensions so far as the visual examination is concerned.

The air is injected into the test tube coaxially while the water is introduced peripherally as mentioned earlier. The inlet pressure at the test section is varied to attain desired flow conditions and was measured with a precise pressure gauge, while the outlet pressure is roughly equal to the atmospheric pressure. In order to measure the two-phase flow rates, a precise injection syringe is installed at the exit of the test section through a injector head. This syringe can collect the two-phase flow coming from the test section and accurately reads out the volumetric flow rates of both air and water. Alternately, a gas-liquid separator is connected to the test section exit, and liquid flow rate was measured by a

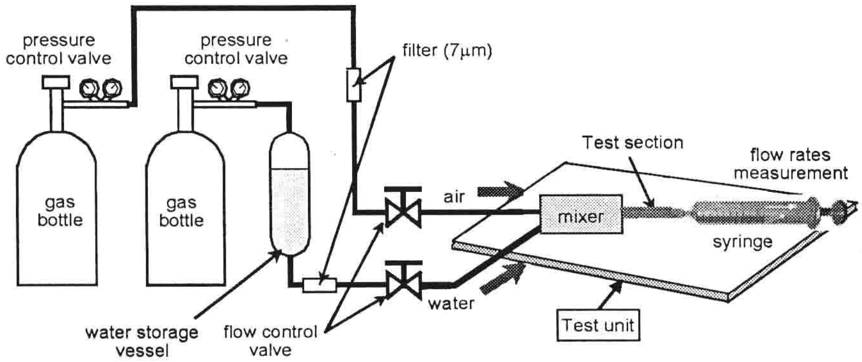

Fig.3 Experimental setup

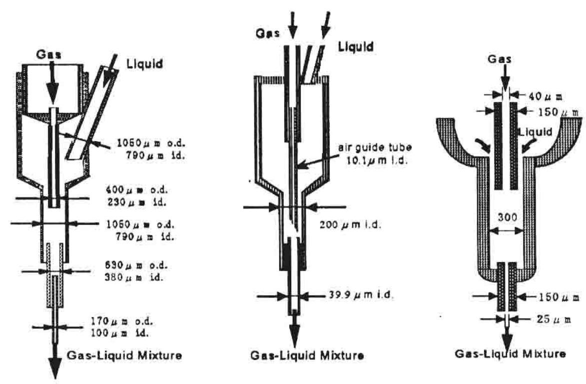

Fig.4 Various designs of mixing section

precise electronic balance.

Figure 6 is the outline of the method of visual observation of micro-channel two-phase flows adopted in this study. The visualization of two-phase flow patterns was realized by use of a microscope which can magnify the images up to 150 times as that of the original size. A high speed camera system was mounted together with the microscope. We used a Redlake Motion Scope HB with recording speed of 30-4000 frames per second and shuttering speed up to 1/10000s, or a Photoron FASTCAM Rabbit with up to 600 frames per second and 1/80000 s, depending on the experimental conditions. Two-phase flow patterns were visualized near the exit of the test section.

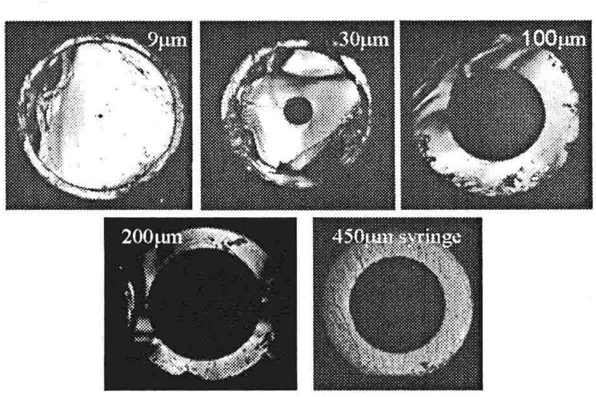

Fig.5 Uniformity of micro-channel dimensions

A water box was used for visual observation in order to minimize the effect of refraction.

The cross sectional average void fraction was calculated and averaged from more than 1000 high-speed video images frame by frame, by assuming spherical bubbles for bubbly flows and axisymmetric flow for slug, liquid ring and annular flows which will be mentioned later (Serizawa et al.[5, 6], Suzuki [11]).

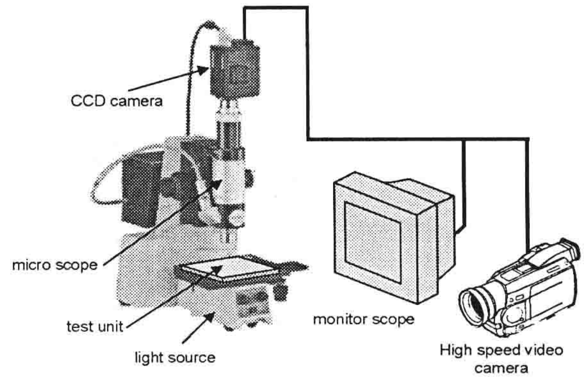

Fig.6 Method of visual observation

TWO-PHASE FLOW PATTERNS

We identified more than several two-phase flow patterns, some of which have never been reported before except by the present author and his coworkers.

Figures 7 ~ 11 show typical two-phase flow patterns observed in air-water flows in a 25μm silica tube (Serizawa et al., [5]), in a 39.9μm quartz tube (Suzuki [11]), in a 80μm quartz tube (Mori [10]), and in a 100μm quartz tube (Serizawa et al. [5-8]) at nearly atmospheric pressure, respectively. For two-phase flow identification, we did not correct for the refraction of light in an image construction. The brighter bands along the centerline of the tube in the figures are due to the refraction in the test tube.

A common feature of two-phase flow patterns observed in micro-channels with different diameter is an existence of liquid ring flow which is reported to have been observed under micro gravity where the surface tension force is dominant (Rezkallah [14]). Bubbly two-phase flow is one of the most difficult flow patterns to be realized in adiabatic gas-liquid two-phase flow in micro-channels and intermittent flows are very popularly encountered. In fact, dispersed bubbly two-phase flow which is very popularly encountered in channels with conventional scales was observed, in the present work, only in a 100μm diameter quartz tube which had been very carefully processed with a soft brush and by mechanical cleaning with ultrasonic vibration alternately in water, ethanol solution and in hydrochloride acid solution, as shown in Fig.11. In other cases, bubbly flows consist of a series of bubble chains as typically shown in Figs.7 ~ 10. Some explanations will be given below for some other two-phase

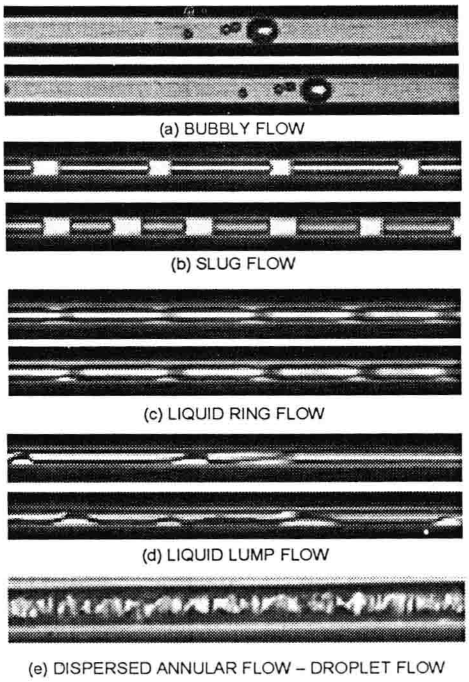

Fig.7 Two-phase flow patterns in a 25 μm silica tube

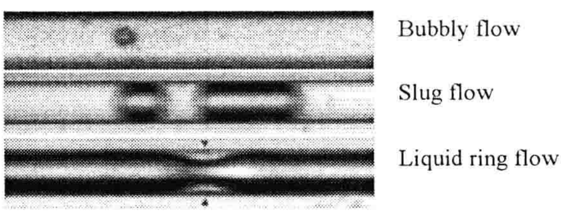

Fig.8 Two-phase flow patterns in a 39.9 μm quartz tube

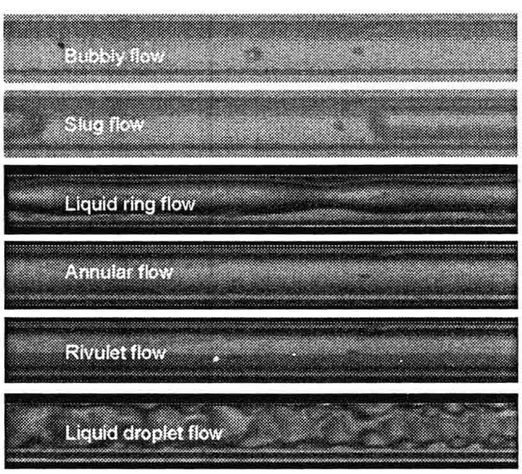

Fig.9 Two-phase flow patterns in a 80μm quartz tube

flow patterns observed in micro-channels.

Slug flow (S): slug flow occurs if the gas flow is high at the tube entrance and the speed of long gas bubbles is not high

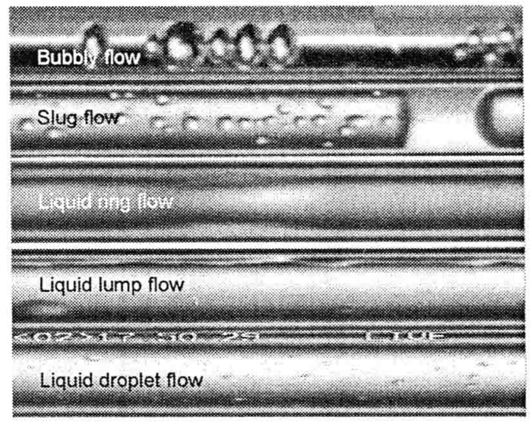

Fig.10 Two-phase flow patterns in a 100μm quartz tube

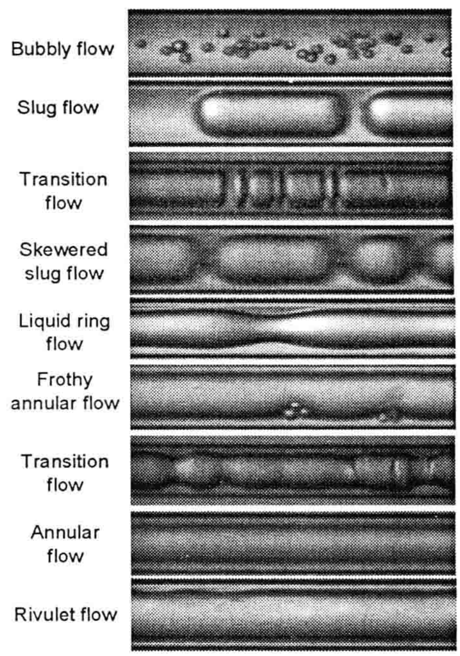

Fig.11 Variation of two-phase flow patterns observed in a clean quartz tube of 100μm

enough to overcome the strong surface tension force of the liquid bridge between them. The surface tension force keeps liquid phase to a slug structure and prevents it from being dispersed as film or dispersed bubbles. It was found that the pressure drop induced by slug flow is very high. This implies that the sliding between gas slug and the tube wall is suppressed and therefore a dry zone may have been developed underneath the gas slug due to a strong influence of surface tension. We succeeded in obtaining an experimental evidence for the formation of dry zones underneath the gas slug. A typical example showing this is demonstrated in Fig. 12. Another interesting finding is that, when the slug bubbles move at very low velocities, liquid droplets remain to stick on the dried tube wall within the slug bubbles as shown in Fig.10.These liquid droplets do not move along the tube wall while the gas slug is moving.

Skewered slug flow (SK): Skewered slug flow is an interesting flow pattern that has never been reported before by