Summary of Research Project
(Ground Research Announcement for Space Utilization)

Title of Project: Experimental and theoretical study of deformation behaviors of gas-liquid interfaces under microgravity
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Abstract Deformation behaviors of the gas-liquid interfaces of liquid bridges and annular films under microgravity were investigated experimentally using drop shafts. The experimental results were compared with those of numerical analysis and simulation.

In liquid bridge experiments under microgravity, the liquid bridge in air was stabilized by AC electric fields tangential to the interface. We succeeded in anchoring the almost cylindrical liquid bridge above the Rayleigh-Plateau limit between two disks. The cylindrical liquid bridge under the unstable condition(in the absence of the AC electric field) broke asymmetrically in the axial direction.

In plug formation experiments in horizontal/vertical pipes under microgravity, the liquid in a pipe formed an annular film and broke into several plugs. The average distance between adjacent peaks on the interface profile was good agreement with the results of a linear stability analysis and numerical simulation of the annular liquid film.

Summary of Research Results
1. Introduction Microgravity is one of the features of the space environment, the interfacial behavior plays an important role in multiphase flows, since the buoyancy-driven convection is suppressed. Therefore, numerous studies on interfacial deformation and phenomena such as Marangoni flow have been reported. We also have carried out the studies on the liquid bridge between disks and two component heat pipe in order to apply the chemical engineering to the space technology.

In many previous studies, it was assumed that the interfacial profile was static. In this study, dynamic behaviors of interfaces on the liquid bridge and annular films under the unstable condition were investigated experimentally and numerically.

2. Experimental Procedures
(1) Liquid Bridge The experimental apparatus for observing a liquid bridge is shown in Fig.1. The liquid bridge was formed between disks(φ 5). The working fluid (castor oil, silicone oil etc.) was supplied through the hole which penetrated the center of the lower disk. The upper disk was vertically mobile using the actuator. In order to stabilize the liquid bridge above the Rayleigh-Plateau limit and suppress the EHD(electrohydrodynamic) convection, an electric field was created axially by applying AC voltage to the electrodes. The microgravity experiments were carried out in MGLAB and JAMIC.

The experiments in MGLAB were preliminary.

In microgravity experiments, by using the digital command and the controller before the falling, a liquid bridge with 0.2D(D was the diameter) was formed, and an AC electric field was created. Under microgravity, the length of the cylindrical liquid bridge was increased by the falling command until it
was above the Rayleigh-Plateau limit. The stabilized liquid bridge was observed by a video camera. When the electric field disappeared (7 sec. after the start time of the falling), the liquid bridge became unstable. The behavior of the gas-liquid interface under the unstable condition was also observed.

(2) Liquid Plugs in Horizontal Pipes  The experimental apparatus for observing liquid plugs in a horizontal pipe is shown in Fig.2. The glass pipe was horizontally installed. The three apparatuses were used in microgravity experiments at HNIRI(Hokkaido Nat. Industrial Res. Inst., Ministry of International Trade and Industry), MGLAB and JAMIC. Each length of the glass pipe with inside diameter 6, 8, 10 was 344, 372, 345mm, respectively. The working fluid was ethanol which got wet in a pipe.

In microgravity experiments, by using the digital command and the actuator before the falling, the direction of the gas-liquid interface was adjusted horizontally. The behavior of the interface deformation and the plug formation under microgravity was observed by a video camera.

(3) Liquid Plugs in Vertical Pipes  The experimental apparatus for observing liquid plugs in a vertical pipe is shown in Fig.3. The glass pipe was vertically installed. The six apparatuses were used in microgravity experiments at MGLAB and JAMIC. Each length of the glass pipe with the inside diameter 4, 6, 8 was 300 (the MGLAB experiments) and 230mm (the JAMIC experiments), respectively.

In microgravity experiments, by using the digital command and the feeder, the working fluid (ethanol) was supplied from the top of the pipe. Under microgravity, it stopped supplying the fluid. The behavior of the interface deformation and the plug formation under microgravity was observed by a video camera.

(4) Numerical Simulation of the Deformation Behavior of an Annular Film in a Pipe  The finite-difference simulation of the dynamic behavior of an annular film with a uniform thickness in a pipe under microgravity was carried out. The small perturbation was added initially at the interface profile. The Navier-Stokes equations were solved in boundary-limited coordinates and by means of the BSMAC or the SMAC method.

3. Research Results
(1) Liquid bridge  The behavior of the liquid bridge with 3.3D under microgravity at JAMIC is shown in Fig.4. The value of AC voltage was 25kV (peak-to-peak). The liquid bridge above the Rayleigh-Plateau limit (π D) in air was stabilized by an AC electric field (see Fig.4(a)), and kept its profile cylindrical (see Fig.4(b)). The unstable liquid bridge in the absence of electric field was deformed (see Fig.4(c)) and broke asymmetrically in the axial direction (see Fig.4(d)). After the breakage, the volume of the drop under the upper disk differed much from that on the lower disk.

The stability limit of the cylindrical liquid bridge in AC electric fields was shown in Fig.5. The solid curve is drawn from the result of a linear stability analysis by González et al. (J. Fluid Mech., vol.206, pp.55-561 (1989)) for castor oil bridge in air. In their analysis, it was assumed that the liquid bridge was perfectly dielectric, and that the Navier-Stokes equation included the electrostriction force term. The results of our JAMIC experiments were reasonable agreement with that of González’s analysis.

(2) Liquid Plugs in a Horizontal Pipe  The liquid plugs formed in a horizontal pipe (φ 8) under microgravity at the MGLAB are shown in Fig. 6. The core diameter (d4) was calculated from the
liquid volume fraction on the assumption that an annular film was formed with a uniform thickness at the transition to microgravity. The experimental results of the average distance between adjacent peaks on the interface profile are shown in Figs. 7, 8. The broken line is drawn from the result of a linear stability analysis by Takamatsu et al. (Microgravity Sci. Tech., vol.12, pp.2-8 (1999)). Our experimental results were reasonable agreement with that of Takamatsu's analysis. The discrepancy between the results was probably caused by the lack of uniformity of the film thickness.

The pitch of liquid plugs was also measured. The average pitch was generally longer than the average distance between adjacent peaks on the interface profile due to the combination between plugs.

(3) Liquid Plugs in a Vertical Pipe  The liquid plugs formed in a vertical pipe(φ 4) under microgravity at MGLAB are shown in Fig. 9. The core diameter(dg) was calculated from the flow rate under normal gravity. The experimental results of the average distance between adjacent peaks on the interface profile is shown in Fig. 10. Our experimental results were good agreement with that of Takamatsu’s analysis(broken line in Fig.10), since the thickness of the falling film was uniform.

(4) Numerical Simulation of the Deformation Behavior of an Annular Film in a Pipe
An initial profile(T=0) of the gas-liquid interface with the perturbed film thickness in a pipe is shown in Fig. 11. The profiles of the gas-liquid interface at T = 2.0 and 2.6 are shown in Figs. 12, 14, respectively. The HSMAC method was used in the numerical simulation. The average distance between adjacent peaks on the interface profile was almost constant regardless of the elapsed time(T). The power spectra of the interface profiles in Figs. 12, 14 are shown in Figs. 13, 15, respectively. Each power spectrum was calculated using the Fourier transformation. The frequency of the highest peak in the power spectrum was almost constant.

For various core diameters, the numerical results of the average distance between adjacent peaks on interface profile in a pipe(φ 8) is shown in Fig. 16. The results of numerical simulation were also good agreement with that of Takamatsu(broken line in Fig.16).

4. Comments on Space Experiments
(1) Liquid Bridge  In the space shuttle experiment by Burcham and Saville (J. Fluid Mech., vol.405, pp.37-56 (2000)), castor oil bridge in dielectric gas (SF6) could not be stabilized in AC electric fields. They suggested that the behavior of bridges with gas-liquid interfaces differed from that with liquid-liquid interfaces. Since our microgravity experiments were carried out only using the drop shafts, further studies are necessary to clarify the behavior of the gas-liquid interface in electric fields under microgravity.

(2) Liquid Plugs in a Pipe  In space experiments, the behaviors of the interface deformation and the plug formation in a pipe are observed under the quasi-static condition.

5. List of Publication
Proceedings