Chapter 1   Fluid Experiments in Microgravity

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1. Introduction

With the advent of the International Space Station (ISS), the subject of microgravity research has become increasingly important. The fact that it is possible to perform scientific research under an extended period of microgravity gives us many new and different opportunities to increase our knowledge. Microgravity research is dispersed over a number of disciplines but the underlying and unifying basis for new aspects in microgravity is gravitationally modified bio-phyico-chemical transport phenomena. This means that the effects of fluid flow and heat and mass transfer on physical transformations and biological and chemical reactions will be different in microgravity. Since such transport phenomena are important in the chemical, pharmaceutical, and biotech industries as well as in materials processing, the scope of the microgravity research program will be broadened if it is directed to understand such phenomena in order to develop a knowledge base for the applications. For this reason numerous experiments on fluid physics and transport have been performed in space since the days of the Skylab. When the ISS becomes fully operational in the near future, it is expected that our knowledge base will expand substantially. In order for this to happen, we must plan the utilization of the ISS carefully.

Potential advantages of a microgravity environment include reduction of buoyancy, reduction of phase separations and particle settling, and levitation and isolation of large samples. Therefore, much research is anticipated in various areas such as interfacial phenomena (capillary phenomena, drops and bubbles), multi-phase flows (boiling and condensation, flow regimes and transitions), combustion (fire safety, understanding of basic combustion processes, development of advanced propulsion systems), biotechnologies (protein growth, bioreactors, and life support systems), crystal growth, and containerless processing.

Recently in the US, in order to prioritize the subjects to be investigated aboard the ISS, NASA assembled a committee called the Research Maximization and Prioritization (REMAP) Task Force. The committee's report was made public in July

2002 [1]. It recommends that "NASA support outstanding basic scientific research programs that address important questions in the physical and biological sciences, and which require long-term experiments on the ISS, based on their intrinsic scientific value." Various subjects were ranked from the first priority to the fourth priority. In the area of physical sciences, the following subjects are ranked as the first priority: phase transformation, condensed matter, fundamental laws, kinetics structure and transport, fluid stability and dynamics, energy conversion, and cell and molecular biology. As noted, various subjects related to fluid mechanics and heat transfer are included in the first priority. The justification by the REMAP committee for the first priority research include: to reveal fundamental laws of nature, to understand the role of gravity, and the existence of research community for quality ground- and flight-based research.

NASA is already thinking beyond the Space Station, namely trips to the Mars. The ISS will be maintained by supplies from the earth. The Mars trip, which takes nearly 10 months just for a round trip, necessitates self-sufficiency, so it requires completely new mission-enabling technologies. Again, we need to have a solid knowledge base for fluid transport in microgravity in order to develop those technologies.

Many crystal growth experiments have been performed in microgravity because it was believed that gravity and buoyancy prevented us from growing better and larger crystals on earth. However, buoyancy is not completely suppressed in space, and, moreover, there exist some other types of driving forces which are usually overwhelmed by buoyancy on earth but become important in microgravity. For example, g-jitter aboard spacecraft can generate bulk fluid motions due to g-jitter induced buoyancy as well as free surface motions if liquid free surfaces are present. In particular, Marangoni convection has received much attention since the early days of space experiments. Since this author has been and still is involved in microgravity experiments on Marangoni convection, this subject is the main topic of the present article.

2. Marangoni Convection

Ostrach [2] studied various types of fluid flows that could occur under low-gravity conditions and pointed out that Marangoni convection is one of the important flows. Marangoni convection is induced by surface tension gradients along a liquid free surface as a result of temperature and/or concentration gradients. The subject of Marangoni convection has been discussed in this JSUP series by Imaishi [3]. One well-known example of Marangoni convection is so-called 'wine tears'. In a wine glass, due to Marangoni convection caused by the evaporation of alcohol, the wine climbs along the glass as a thin film up to a certain height and accumulates. Eventually gravity causes the wine to flow down in the shape of tears. Surface-tension-induced flow due to temperature gradient is also called thermocapillary flow. Surface tension generally decreases with increasing temperature. As illustrated in Fig. 1, when there exists a temperature variation along a free surface, a fluid element on the surface is pulled towards the colder region. This shear force induces bulk fluid motion through viscosity. We normally distinguish thermocapillary flow from a resultant flow of Marangoni instability that could occur when temperature gradients are imposed normal to a free surface. Marangoni convection is known to play important roles in many applications, such as crystal growth from melt, droplet migration, boiling heat transfer, micro-welding, bio-fluids engineering, etc. In particular, Marangoni convection in the containerless processing method called the float zoning has been given much attention in the past because the technique is considered to be a potentially important method in microgravity applications. Since no container is used for confining the melt, the technique allows zone melting without crucible contamination. However, the melt has a free surface, which, coupled with temperature and concentration variations in the melt, induces Marangoni convection. Crystals have been grown in microgravity by this method. However, these experiments have shown a banded structure and striations in the finished crystals. The underlying cause of these striations seems to be a time-dependent crystal growth speed that is brought about by the temperature fluctuations in the melt. It is important, then, to understand what causes the temperature fluctuations in order to grow high quality crystals in space.

Many experiments have been performed in the so-called half-zone configuration in which a liquid column is suspended between two differentially heated ends (Fig. 2). The configuration roughly simulates half of the float zone melt. For the ease of experiments, high Prandtl number (Pr) fluids, mainly silicone oils, were often used as the test liquids. Pr is the ratio of kinematic viscosity to thermal diffusivity. Very high

Pr (Pr >> 1) fluids are usually very viscous, while highly thermally conducting fluids, usually liquid metals, have low Pr (Pr << 1). Crystal melts tend to have low Pr, so experiments with high Pr fluids do not actually simulate the float zoning. Nevertheless, tests with high Pr fluids are interesting because it was found that the flow becomes oscillatory (time-dependent) under certain conditions. The oscillation phenomenon was first reported more than twenty years ago by Chun and Wuest [4] and Schwabe and Scharmann [5]. Since then, much experimental and theoretical work has been performed on the phenomenon (reviewed by Preisser et al. [6], Masud et al. [7]). However, how and when the flow becomes oscillatory is not yet fully understood. As discussed below, more definitive microgravity experiments are needed to solve this complex problem. It is somewhat unusual that we still do not understand this oscillation phenomenon fully after nearly twenty years of investigations. It is about time to solve this problem once and for all.

In the light of the importance of Marangoni convection in many applications and recognizing also the practical and scientific interest in the oscillation phenomenon, NASDA (National Space Development Agency of Japan), led by Dr. Yoda, assembled a group of researchers from outside NASDA in 1997 to conduct a comprehensive investigation of the subject. The program is intended to demonstrate the potential of microgravity utilization and to promote microgravity utilization as the frontier in microgravity science research. This author joined the group, called the Marangoni Convection Modeling Research group, as the lead scientist. The other outside members included: (in alphabetical order) Professor Imaishi of Kyushu University, Professor Kawaji of Toronto University, Professor Kawamura of Science University of Tokyo, Dr. Kawasaki of IHI Aerospace, Dr. Kuhlmann of ZAMM, and Professor Nishino of Yokohama National University. The group members were chosen to perform experimental (Kamotani, Kawaji, Nishino, NASDA), numerical (Imaishi, Kawamura), and theoretical (Kuhlmann) investigations on Marangoni convection over a wide range of Prandtl number in the half-zone (or liquid-bridge) configuration. The group was specifically interested in delineating the mechanisms of the transition to oscillatory flows. Since its inception, the group met frequently to discuss their findings and to exchange ideas. Much progress has been made by this group so far, which is summarized below.

3. Past Work of Marangoni Convection Modeling Research Group

In order to aid the following discussion, the basic steady flow field in the half-zone configuration is discussed first. As illustrated in Fig. 3, the flow in the liquid column is from the hot to cold walls along the free surface, called the surface flow herein, which is driven by thermocapillarity. The fluid moves in the opposite direction in the bulk region, called the return flow. The resulting flow has an axisymmetric toroidal pattern. With low Pr fluids (Pr on the order of 0.01, for liquid metals), the liquid temperature changes almost linearly from the hot to cold ends. With high Pr fluids, the temperature field gets more distorted as the flow becomes faster: more hot fluid is convected by the surface flow and the return flow becomes cooler. This temperature change by the flow changes the thermocapillary driving force, which, in return, alters the flow. This coupling between the flow and temperature fields is an important feature of thermocapillary flow of high Pr fluid. The importance of convection is represented by a dimensionless parameter called the Marangoni number (Ma): with increasing Ma, the temperature field becomes more distorted and the above coupling becomes more important. Ma divided by Pr is called the Reynolds number (Re = Ma/Pr), which represents the ratio of inertia to viscous forces in the flow. For a given fluid and liquid column dimension, Ma or Re is varied experimentally by changing the imposed temperature difference between the hot and cold walls (ΔT).

In the case of low Pr fluids, both linear stability analysis [8] and numerical simulation [9] show that the initial steady axisymmetric flow changes to steady but non-axisymmetric flow with increasing ΔT as a result of hydrodynamic instability. As the flow becomes faster and thus the relative importance of viscous forces diminishes (or when Re becomes large), it becomes impossible to maintain the axisymmetric flow structure. The transition also depends on the liquid column aspect ratio (Ar = column length/diameter). Ar is of order unity. The critical Re is about 1000 for Ar = 1.0 [8]. Low Pr fluids are generally opaque so that it is not possible to observe this flow structure change directly in experiments. Moreover, the temperature field is only slightly modified by the flow change because Ma is relatively small, less than about 500, at the transition so that the instability also cannot be detected by the temperature measurement.

With further increase in ΔT (or Re) beyond the transition, the flow becomes oscillatory as a result of secondary instability, according to numerical simulations ([9]). The experiments are being conducted with liquid tin (Pr = 0.009) at NASDA. It is noted that thermocapillary flow experiments with low Pr fluids are very difficult because one has to overcome the oxidation at the free surface. According to the NASDA experiment, the second transition occurs at a Re of about 5000 for Ar = 1 [10]. Based on the numerical simulations [11], various oscillatory flow patterns appear: the three-dimensional flow after the first instability twists or rotates around the column axis. The fact that, with increasing ΔT, the flow becomes three-dimensional first and then, with further increase ΔT, the three-dimensional pattern begins to twist or rotate is very similar to the case with natural convection of low Pr fluid in a cylinder that is heated from below [12]. In both cases, as the inertia forces become so strong that the flow overshoots and undershoots in the process of forming the three-dimensional flow structure, resulting in oscillations. Although there exist some discrepancies between the experiment and numerical simulations regarding the critical conditions, especially when Ar is about 0.5 [10], it seems that the oscillation mechanism is reasonably well understood.

Our group is also investigating the flow instability with medium (unit-order) Pr fluids. Fluids used by Kawaji et al. [13] are acetone (Pr = 4.4 at room temperature) and methanol (Pr = 6.9). They tend to evaporate, so we must take special precautions to minimize the evaporation during tests. Nevertheless, the free surface heat loss due to evaporation in the experiment is not small compared to the amount of heat transferred through the liquid so that the basic flow field is very much altered by it. The experimental [13], theoretical [14] and numerical investigations [15] by the group members show that the initial axisymmetric flow becomes oscillatory beyond a certain ΔT, without going through a transition to steady non-axisymmetric flow first as found in low Pr fluids [9]. The experimental data [13] and the linear stability analysis [14] agree regarding the critical condition, as long as the heat loss is included in the analysis. According to the analysis, the transition is due to hydrothermal wave-type instability where certain flow and thermal patterns rotate around the liquid column axis with a phase shift between them. Although the critical condition predicted by the numerical simulation, including the evaporation heat loss, differs from the experimental data [15], our understanding of the oscillation mechanism for medium Pr fluids with relatively large free surface heat loss is satisfactory. Although the oscillation phenomenon appears to be similar to that for high Pr fluid to be discussed later, there is an important difference. Large surface heat loss in the case of medium Pr fluid increases the temperature gradient everywhere along the free surface. Consequently, the thermocapillary driving force exists all along the free surface. In contrast, one important feature of high Pr flow is that the driving force is more concentrated near the hot wall, as discussed below. At present, no experimental data is available for oscillatory thermocapillary flow with negligible free surface heat loss for medium Pr fluid.

Finally, thermocapillary flow of high Pr fluid (Pr $>$ 15) is discussed. As in the medium Pr case, it is known that the initial axisymmetric flow transits to non-axisymmetric oscillatory flow under certain conditions. The photographs in Fig. 4 show typical oscillatory flow structures. For the flow visualization, a small amount of tracer particles are added to the fluid and a laser light sheet illuminates one cross-section. When the flow is steady, the flow structure is symmetric. After the onset of oscillations, the right and left sides in one cross-section are seen to interact strongly. Actually in Fig. 4 this interacting pattern is rotating around the column axis so that the flow pattern on the right rotates to the left half after a half period.

Much data is available from past experiments in this Pr range concerning the critical conditions, mostly taken in normal gravity with small liquid bridges. It is relatively simple to perform tests with silicone oils. However, if we were to plot all of the available data together, the data points would be all over the chart. There are several reasons for this, such as the buoyancy effect, shape effect (the onset of oscillations is known to be very much affected by the shape of the bridge, but the shape cannot be maintained as exactly cylindrical in normal gravity), difference in experimental procedure, and difficulty in detecting the onset of oscillations accurately (which needs some experience). Moreover, since only small bridges can be used on the ground, the data covers only limited parametric ranges.

Since only three dimensionless parameters are mainly important for thermocapillary flow in a confined domain, namely Ma, Ar, and Pr (neglecting buoyancy and assuming a straight cylindrical bridge), the critical condition should be specified by Ma for a given fluid (fixed Pr) and geometry (fixed Ar), called the critical

Marangoni number (Ma_{cr}). Since available ground-based data tends to scatter, as mentioned above, it is not possible to prove the existence of Ma_{cr} with certainty. However, if we include the data taken in microgravity with larger liquid bridges, Ma_{cr} clearly increases with the liquid column size, as shown in Fig. 5. One problem with a large liquid bridge is that it takes a long time to reach thermal equilibrium. Whether the microgravity data in Fig. 5 are in thermal equilibrium is debatable, but in any case, the fact that Ma_{cr} in Fig. 5 varies by more than one order of magnitude suggests that Ma_{cr} does increase with increasing liquid column size.

This author performed extensive experiments on oscillatory thermocapillary flows in cylindrical containers aboard the Spacelab in 1995 under the sponsorship of NASA [16,17]. The experiment was called the Surface Tension Driven Convection Experiment (STDCE). Although the configuration of STDCE is different from the half-zone configuration, the question of whether Ma_{cr} exists or not is still valid in that configuration. STDCE was a very interactive experiment in that the astronaut operator and the scientists based on the ground were all involved in operating the experiment and identifying the onset of oscillations. This was important because the oscillation frequency was as small as 0.06 Hz (17-second period) so that it was very difficult to detect a small flow structure change after the transition. It was a very time-consuming experiment for the astronauts (a total of about 90 hours of their time), but we were able to perform the tests as if we were doing them on the ground. Therefore, we were able to adjust the rate of heating of the test fluid in-situ and determine the critical conditions that were not affected by the heating rate. As shown in Fig. 6, even in the STDCE tests it was found that Ma_{cr} increased with increasing container dimension, as in the half-zone case. If Ma is the only important parameter for a given Pr and Ar, the principle of dimensional analysis tells us that Ma_{cr} should not vary with the container dimension. Clearly, the critical condition cannot be specified by Ma alone, which means that we have to consider an extra feature to explain it.

Linear stability analysis was performed also for flow of high Pr fluid, but it is found to be very difficult to obtain accurate results (grid-independent results) due to the presence of relatively thin temperature boundary layers along the hot and cold walls [18]. Nevertheless, the analysis shows hydrothermal wave-type instability at a Ma_{cr}. If the analysis is correct in predicting Ma_{cr}, then there exists a substantial discrepancy between the theory and experiments for high Pr fluids.

This author has proposed a physical model of oscillations for high Pr fluids, different from the linear stability model, which conjectures the importance of dynamic free surface deformation (DSD) [19]. Fluid motion always deforms a free surface. However, in the present problem the dynamic free surface deformation during oscillations is very small: we can see it only after large magnification, so its importance has been neglected by many investigators. However, one important feature of thermocapillary flow of high Pr fluid is the existence of very thin thermal boundary layers in the range of Ma where the oscillations are observed. Then, the deformation is not small compared to the boundary layer thickness and thus it could alter the boundary layer and the flow driving force. The model assumes that the oscillation phenomenon is a non-linear dynamical process in which the driving force is continuously altered by the interactions among the free surface deformation, and the velocity and temperature fields. According to this model, a surface deformation parameter called S-parameter specifies the onset of oscillations. The S-parameter correlates available critical conditions well, as found in the STDCE tests (see Fig. 7). Nishino et al. [20] are investigating this three-way coupling experimentally. However, to show directly that the dynamic free surface deformation is indeed important in the oscillation mechanism is very difficult because we cannot control the deformation experimentally. For this reason, Kawamura et al. [21] are investigating oscillatory thermocapillary flow of high Pr fluid numerically including dynamic free surface deformation.

It was found recently that the air motion around the liquid column, which is mainly due to buoyancy associated with the heating and cooling arrangement of the experiment, has a strong effect on the onset of oscillations [22]. The airflow is relatively weak, on the order of 1 cm/s, but it is now known that the heat loss at the liquid free surface associated with the air convection stabilizes the flow significantly. Many experiments have been conducted in the past near room temperature. The work by Kamotani et al. [22] shows that the heat loss effect is significant even in room temperature tests and that when the heat loss is minimized, the critical ΔT is much higher than that obtained in room temperature tests. Therefore, we can use available data on the critical conditions only when the heat loss effect is included.

After so many years of investigations on the oscillation phenomenon, we are now forced to look at this subject quite differently. This also shows that it is necessary to conduct microgravity experiments where the air convection is much reduced. Compared to the evaporation heat loss in the case of medium Pr fluid, this heat transfer to the surrounding air is generally much smaller so that its effect on the temperature field in the liquid is much less. Then, this heat loss is considered to affect the oscillation mechanism directly without changing the basic flow field. The same is true for DSD. Therefore, the heat loss effect must be augmenting the DSD effect. This heat loss effect seems to support the oscillation mechanism involving DSD. One evidence for this is shown in Fig. 8, where the S-parameter at the critical condition is plotted against the dimensionless heat loss rate (Bi in Fig. 8, Biot number, represents the dimensionless free surface heat loss). The figure shows that the S-parameter and the heat loss together can specify the critical condition.

Based on these past investigations, it is clear that we need to do more work with high Pr fluids to understand the oscillation mechanism. This leads us to the proposed Space Station experiment on this subject.

4. Proposed Space Station Experiment on Marangoni Convection

In view of the current status of our understanding of Marangoni convection, the Marangoni Convection Modeling Research group decided to submit a proposal in response to the first International Announcement of Opportunity for Microgravity Research (IAO) in 2001 to perform microgravity experiments on the oscillatory thermocapillary flow of high Pr fluid. The main objective is to determine the cause of the oscillation phenomenon, more specifically to decide which parameter, Ma or S-parameter, specifies the critical condition. If the S-parameter is the appropriate parameter, we want to investigate the dynamic free surface deformation during oscillations. The proposed experiment is to be performed in the Fluid Physics Experiment Facility (FPEF) which is being developed by NASDA.

The comments by the international science reviewers reflected the ongoing controversy between the two ideas about the oscillation mechanism, but overall the proposal received favorable reviews. After the science review was the technical review by NASDA. Although there are several engineering problems that need to be addressed (some will be discussed later), none were showstoppers. After these reviews and the program review, our proposal was selected as a candidate for flight experiment. We are now in the definition phase in which we respond to the various comments from the reviewers and baseline the experiment and procedure in detail. Currently we are near the end of this phase. After the definition phase we will come up with a document detailing the experiment. After that we will go through a review to determine whether we can go into the development phase where various preparations for flight experiment will be made. The design of the proposed experiment, as is conceived now, is described below.

The configuration of interest is the half-zone configuration. The test fluid is 5 centistokes silicone oil (Pr = 65 near room temperature). Three different diameters (D) will be used: D = 5, 10, and 30 mm. The smallest diameter is for direct comparison with ground tests. The largest diameter is determined by several constraints such as the stability of liquid bridge against g-jitter and the heating time to reach thermal equilibrium. The aspect ratio is set at 0.5, 1 and 2 (plus 0.3 for D = 5 mm). The main tests will be done with flat free surfaces but some tests will be performed with concave free surfaces. The exact test matrix is still being worked out. The matrix will be made flexible so that if time allows (how much time our experiment will get in the final timeline of the Space Station is not clear at present), we will be able to run more cases. The proposed experiment takes advantage of the FPEF's exchangeability of experiment cell (EC), which permits the use of custom-built ECs. Three ECs will be built for three different diameters.

The flow will be visualized by adding tracer particles to the fluid and observing their motions. In the case of 30 mm diameter, the hot wall is made of sapphire in order to observe the flow through it by three video cameras and construct the flow structure in 3-D. With other diameters the flow will be observed from the side. The temperature field in the fluid will be investigated by a thermocouple inserted through the cold wall. The free surface temperature distribution is measured by an IR camera. The most important aspect of the experiment is the measurement of DSD during oscillations. DSD is expected to be on the order of a few μm so that an accurate measurement method is required. Nishino et al. [23] have developed a microscopic imaging displacement meter (MIDM) for the proposed experiment to measure DSD with an accuracy of ±0.15 μm.

We will pay special attention to the heating rate when performing the experiment. The difference between Ma and S-parameter concerning the critical temperature difference increases with increasing liquid column size. It is estimated that there is a substantial difference in the critical temperature difference for the 30 mm liquid column, so that we will be able to determine which parameter is more appropriate. The physical model represented by the S-parameter conjectures certain phase relations among the dynamic free surface deformation, and the velocity and temperature fields in the region near the hot wall called the hot corner. It also predicts a scaling law for the amount of free surface deformation in the hot corner near the onset of oscillations. This hot corner is very important in the case of high Ma flow of high Pr fluid, because this is the region where the flow is mainly driven. For this reason we will focus on the flow in the hot corner in the experiment. We plan to validate (or invalidate) the S-parameter model by testing its basic conjectures. The proposed experiment is somewhat similar to the STDCE experiment in the basic concept, but the main difference is the emphasis of the proposed experiment on the free surface deformation and the phase relation in the hot corner.

One difficult problem we face is that if dynamic free surface deformation is important in the oscillation mechanism, will g-jitter-induced free surface disturbances affect the oscillation phenomenon significantly? Based on our STDCE experiments, it is unlikely that the onset of oscillations will be affected appreciably by g-jitter and several reasons for this are given in [16]. Then, the next problem is how to distinguish the organized free surface deformation associated with flow oscillations from the g-jitter-induced free surface disturbances experimentally. G-jitter excites mostly resonant waves of the free surface. The resonant frequencies are known to be at least one order of magnitude larger than the oscillation frequencies, so it is possible to distinguish those waves. We are still working on this problem. During the experiment we will monitor g-jitter near the experiment site.

If the experiment passes the next review and is allowed to proceed to space, it is currently estimated that we will conduct the experiment in the JEM around the year 2006, depending on the Space Station progress. We still have some time before the flight time, but it gives us more time to improve the experiment.

5. Remarks on Microgravity Experiments

Based on this author's past and present experiences with space experiments, I would like to mention a few things about space experiments, especially fluid experiments.

It is important to note that there are several constraints in designing a space experiment: safety (which is usually very severe), space (which is very limited), power consumption, sensitivity to g-jitter, ability to withstand the launch load, and limited help from astronauts. Unlike experiments such as crystal growth experiments, fluid experiments generally require nearly continuous observation of moving fluid during a test, which greatly complicates the experiment. The downlink capability is usually limited so that scientists on the ground cannot observe everything they want to observe as the test proceeds. Experiments must be performed in an existing experiment facility aboard the Space Station, which specifies the envelope of the experimental modules. Therefore, one has to keep in mind that a space experimental system is much different from the original ground based system. It is a challenge for the scientists and engineers to design a space experiment to accommodate most of the scientific objectives. Nevertheless, many of the fluid and heat transfer experiments performed in space in the past are not up to par with similar ground-based experiments. We must stride to improve this situation for the sake of better scientific return. We also must develop mechanisms to increase the quality of scientists participating in the space programs.

Mainly due to these constraints, it is quite expensive and time-consuming to design and fabricate a space experiment. Therefore, the experiment objective must be well justified, which usually means it must be carefully peer-reviewed. Moreover, there is usually a considerable time lag between the science definition stage and the final space experiment, so the scientific importance must survive this long waiting period. Also, any scientist who wants to conduct an experiment in space must be very patient. In fact, the afore-mentioned REMAP report [1] recommends that "NASA must reduce the time between experiment selection and flight for research investigations", because current long lead time discourages excellent researchers from participating in space programs and is a major concern for commercial partners.

Based on this author's experiences, Japan, the US, and Europe are developing their space experiment capabilities more or less independently. We need to exchange technical information more often for better science and for reducing development time and cost of each experiment.

The g-jitter effect must be taken into account in fluid experiments with free surfaces. On earth, gravity helps to contain liquid, but in much reduced gravity the containment is lost easily, especially with wetting fluids like silicone oil. Even when the fluid is contained, its free surface is always disturbed by g-jitter to a certain extent. More information is becoming available concerning the g-jitter aboard the Space Station, which helps experiment designers.

The Space Station will become fully operational soon (although its final configuration is not completely settled at present) and will stay in space for an extended period of time. It is an expensive but exciting laboratory. Let us utilize it wisely.

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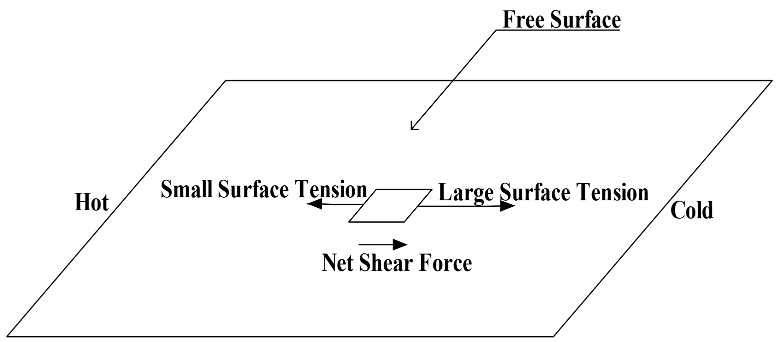


Figure 1 Illustration showing thermocapillary driving force.

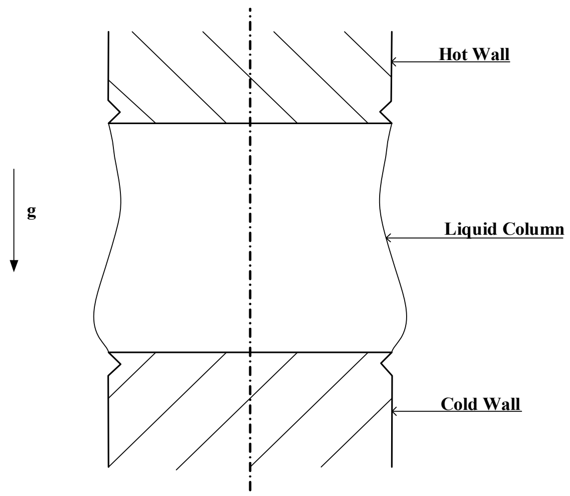


Figure 2 Half-zone or liquid bridge configuration.

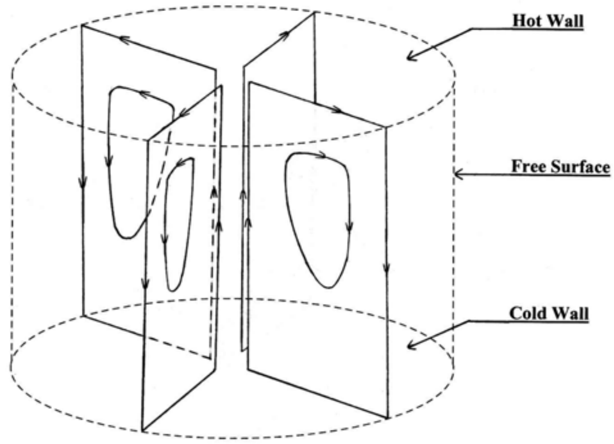
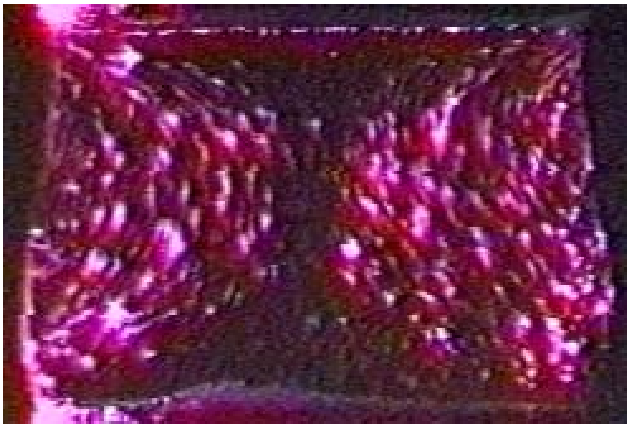
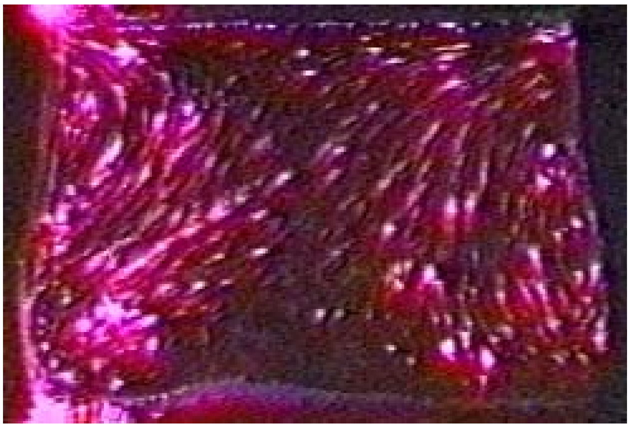


Figure 3 Sketch of steady thermocapillary flow in half-zone.



(a) Steady flow

(b) Oscillatory flow



(c) Oscillatory flow

Figure 4 Steady and oscillatory flow patterns: (b) and (c) are a half cycle apart.

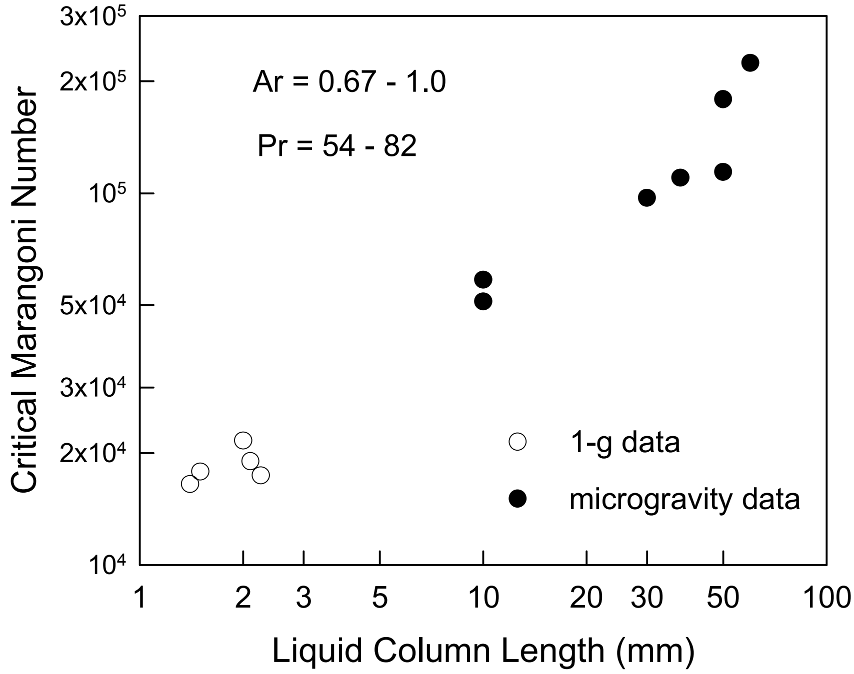


Figure 5 Critical Marangoni numbers for various liquid column lengths for half-zone configuration.

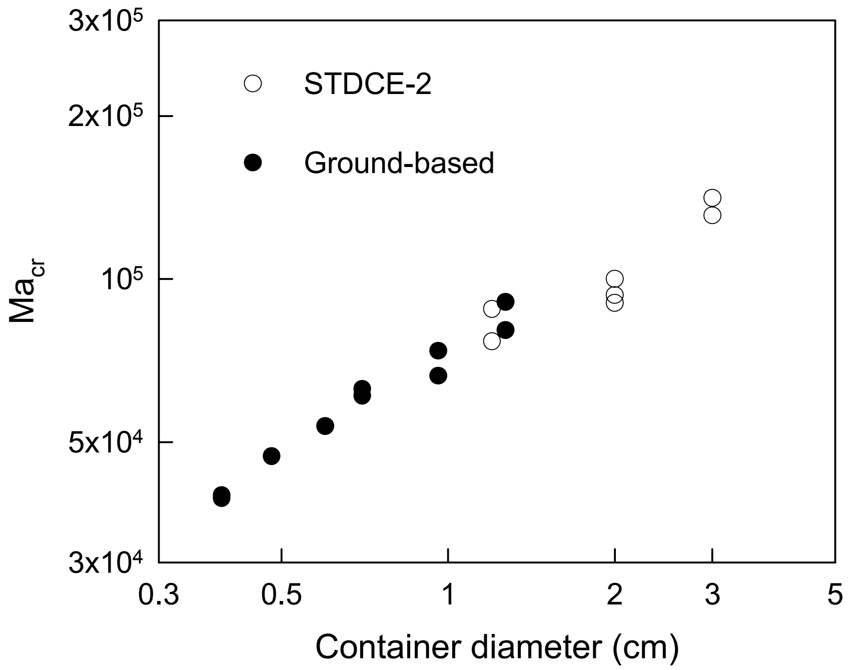


Figure 6 Critical Marangoni numbers for various container diameters for STDCE configuration.

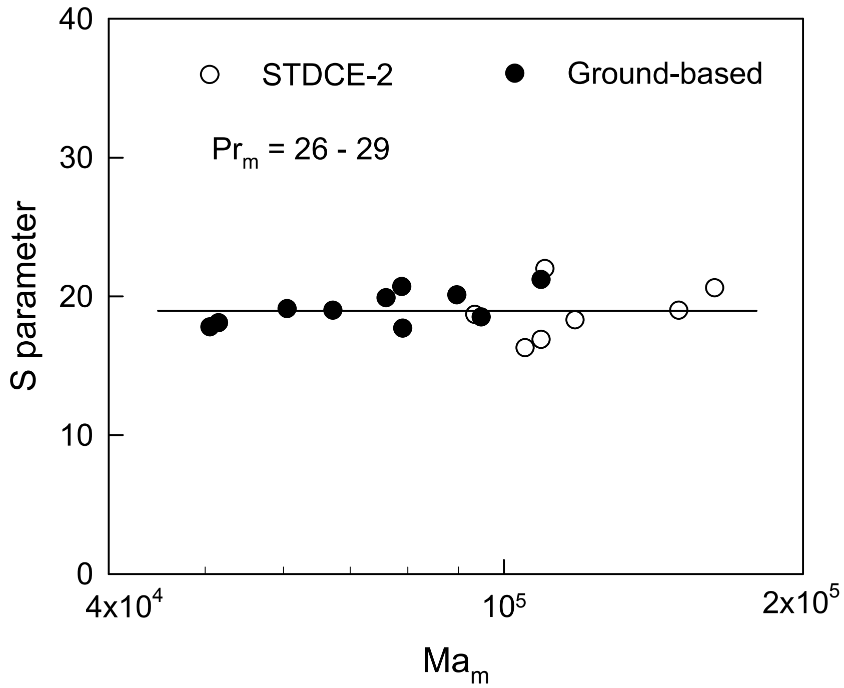


Figure 7 S-parameter at critical condition for STDCE configuration.

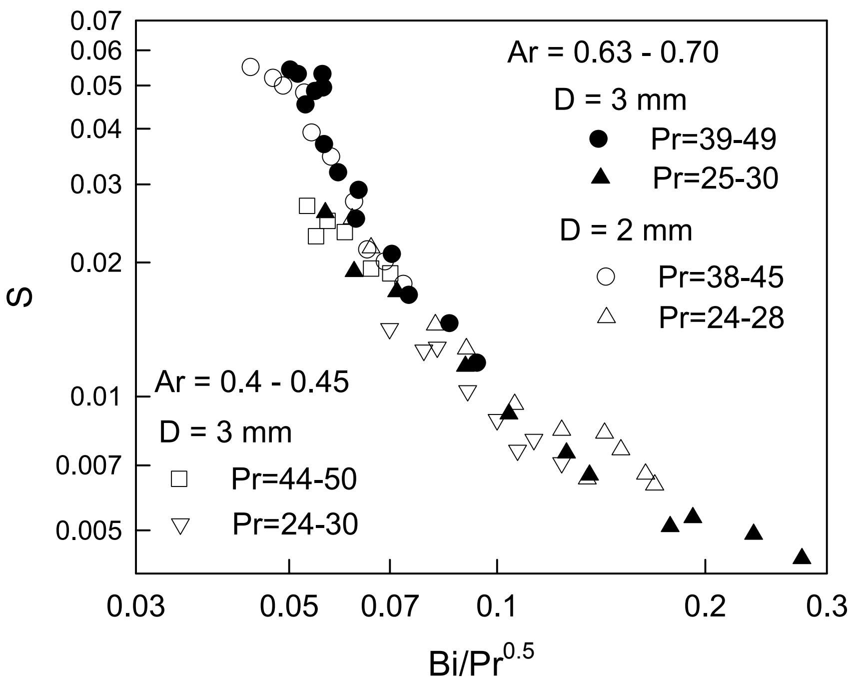


Figure 8 S-parameter as a function of modified Biot number for half-zone configuration.