OSCILLATORY THERMOCAPILLARY FLOW EXPERIMENT

(OTFE)

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ABSTRACT

An experiment was performed on oscillatory thermocapillary flow in the Glovebox aboard the USML-1 Spacelab which was launched in July, 1992. Cylindrical containers of 1 and 3 cm in diameter were used. Silicone oils of 2 and 5 cSt viscosity were the test fluids. The fluid was heated by a cylindrical heater placed along the centerline of the container. The diameter of the heater was 10% of the container diameter. The fluid motion was studied by flow visualization. Although oscillations were observed briefly, bubbles generated in the fluid during the experiment disturbed the flow substantially so that the critical temperature differences could not be determined.

INTRODUCTION

One unique aspect of a low-gravity environment is that surface tension becomes a dominant force and can generate significant flows and associated heat and mass transfer. Although there is both experimental and numerical evidence of steady and transient thermocapillary flows, the detailed nature and extent of oscillatory flows under a variety of conditions remains to be determined as does some of the basic physics, which is not completely understood. In a one-g environment the flow coexists with buoyancy driven flow and is usually overshadowed by it except for flows in very small dimensions.

More than a decade ago German scientists showed the existence of a surface tension induced oscillatory flow state. Because the mechanism for this oscillation phenomenon involves complex physics and cannot be studied easily either analytically or numerically, experimental study of this problem has become the subject of significant scientific importance. Extensive research has been conducted both terrestrially and in space to determine the onset conditions for this oscillatory state.

Much of the past work on oscillatory thermocapillary flow has been done in the so-called half-zone simulation of floating zone melting in which a liquid column is suspended vertically between two differentially heated metal rods. High Prandtl ($Pr > 5$) fluids have been used to simplify the experiments. Schwabe and Scharmann (1979), Chun and Wuest (1979), Chun (1980a,1980b), Schwabe et al. (1982), Preisser et al. (1983), Schwabe et al. (1990), Velten et al. (1991) all experimentally studied oscillatory thermocapillary flow. They all assumed that for given Pr and zone dimensions there is a critical Marangoni number (Ma_{cr}) beyond which oscillations occur. Ma_{cr} was found to be about 10^4 for high Pr fluids in the ground-based tests. However, in the thermocapillary flow experiment on the D-1 mission by Napolitano et al. (1986) with a large (diameter = 6 cm) half-zone no oscillations were found, although Ma was as large as 4×10^5. Monti and Fortezza (1991) conducted half-zone experiments with silicone oils (1.8 cm diam) aboard sounding rockets. The values of Ma_{cr} were found to be at least one order of magnitude higher than 1-g values. Clearly the use of Ma_{cr} to characterize the onset of oscillations is not appropriate. Also, Kamotani et al. (1984) investigated the onset of oscillations under various conditions. They found that Ma alone cannot specify the onset of oscillations and suggested the flexibility of the free surface to be another important factor controlling the onset. It was suggested that a coupling among the velocity and temperature fields and the free surface deformation were responsible for the oscillations. Based on that idea a surface deformation parameter S was proposed. The parameter S correlates well the onset conditions measured under various conditions with high Prandtl fluids (Ostrach et al. 1985).

Theoretically the transition to oscillatory thermocapillary flow in the half-zone configuration has been treated as a form of hydrodynamic instability with an undeformable free surface (Xu and Davis 1984, Shen et al. 1990, Neitzel et al. 1991, 1993). In all those analyses the models do not accurately simulate the actual situations and, moreover, because of the assumption of undeformable free surface the instability criteria are based on Ma, which does not agree with the experimental results discussed above.

Much less information is available on oscillatory thermocapillary flow in other configurations. Lee and Kamotani (1991) studied the oscillation phenomenon in a rectangular container. Kamotani et al. (1992) studied the oscillation phenomenon in a circular container with a cylindrical heater placed along the centerline. That experiment showed that the S parameter can correlate the onset conditions and that the flow structure during oscillations is quite different from that in the half-zone configuration. An organized three-dimensional free surface motion was observed.

Despite all the past work the importance of the deformable free surface is not yet fully understood and our physical model for the oscillations and the S parameter need more experimental confirmation especially in microgravity tests. The Surface Tension Driven Convection Experiment

(STDCE) was designed to study thermocapillary flow in microgravity but its main objective was to investigate steady and transient (non-oscillatory) flow.

Therefore, the Oscillatory Thermocapillary Flow Experiment (OTFE) was conceived to study oscillatory flow in the Glovebox aboard USML-1.

The OTFE was designed to measure the conditions for the onset of oscillations in circular containers. The ranges of Ma and S were chosen to obtain the oscillatory state. 1 and 3 cm diameter cylindrical containers were used with 2 and 5 cSt silicone oils as test fluids. A cylindrical heater was placed at the center of each container with its diameter equal to 10% of the container diameter. The flow was studied by flow visualization. At present we have not received a complete set of video tapes containing the flow visualization and temperature data, so the present paper is based on a preliminary analysis of the data.

I. EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental configuration of the OTFE was the CT configuration of the STDCE but the test fluids and the chamber sizes were different. 1 and 3 cm diameter chambers were used in the OTFE with 2 and 5 cSt viscosity silicone oils as the test fluids. The OTFE consisted of four separate modules, each accommodating one chamber diameter and one fluid viscosity. Each module was configured around a base plate. The module is sketched in Fig.1a and its cross-section showing the test chamber is drawn in Fig.1b.

The top of each plate consisted of a reservoir and piston type pump connected to the test chamber via small diameter copper tubing. The reservoirs are constructed of Lexan to provide optical access. Small tracer particles were mixed with the fluid in the reservoir for flow visualization. A small ball bearing was also placed in the reservoir to provide a method to mix the particles homogeneously in the fluid prior to operation. There were two valves which isolated the reservoir which were opened prior to filling. Each test chamber was cylindrical and constructed of copper with a coaxial resistive heating element. The diameter of the heater was 10% of the chamber diameter as in the STDCE. The bottom wall was made of ceramic. The resistive element was sealed into the ceramic using a fillet of high temperature epoxy. A knife sharp 90 degree edge was machined into the test chamber wall to retain or 'pin' the fluid. Because there was no active cooling of the side walls, the mass of the copper chamber was sized appropriately for the amount of heat produced by the heater. The lid to the test chamber was also Lexan with an anti-reflective coating to reduce reflections. The internal walls of the test chamber were blackened to reduce unwanted reflections. The entire fluid system on the base plate was a closed system. The air displaced from the chamber during filling filled the gap created behind the piston. The test chamber was instrumented with two type-T thermocouples, one placed just under the pinning edge and one protruding into the fluid. The latter thermocouple was positioned at the half-radius location in the radial direction and one-third of depth away from the free surface in the axial direction. The heater also had a type-T thermocouple placed at the same height as the thermocouple in the wall.

The heater and thermocouple leads were routed through the base plate to a printed circuit board on the other side. This circuit board contained signal conditioning electronics and LED displays for three thermocouples and a heater power control circuit. The LEDs had a 10 Hz display rate. The power to the heater was varied via a transistor circuit. As the gate voltage of the transistor was increased, current flowed through the heater, thus increasing the power to the heater. The ranges of heater power available were 0-10 W for 1 cm chambers and 0-13 W for 3 cm chambers. The thermocouple displays and the transistor circuit utilized the Glovebox ±12 VDC line while the heater was powered using the Glovebox +5 VDC line.

The OTFE utilized two video signals for data recording on Spacelab VCRs. A black and white camera with 1:1 lens was attached to the PCG microscope to view, through the top of the Glovebox, the flow field in the chamber and a color camera with 1:1 lens was attached to the door to view the LED displays. These two video signals comprised the OTFE data. Therefore, both signals were recorded simultaneously and time stamped to insure that they can be temporally correlated. From these video records, the time of the transition from steady to oscillatory flow, as observed on the flow data, can be correlated with the temperature data yielding the critical temperature difference ΔT_{cr}. Also, the bulk flow temperature can be plotted as a function of time, yielding the oscillation amplitude and frequency. The overall experimental arrangement is sketched in Fig. 2.

An outline of the experimental procedure was as follows.

1. Unstow module and mix particles.
2. Configure module in Glovebox and power up (Fig. 2).
3. Configure video cameras.
4. Fill chamber.
5. Increase power in a stepwise manner while watching for oscillations.
6. After oscillations are observed, decrease power below point; increase power in smaller steps until oscillations are reached again: continue procedure transition is precisely defined.
7. Power down and wait for module to cool.
8. Empty chamber.
9. Reconfigure Glovebox with another module or stow Glovebox hardware.

II. PARAMETRIC RANGES

The important dimensionless parameters for the present experiment are : Ma (Marangoni number) = $\sigma_T \Delta TR/\mu\alpha$, Pr (Prandtl number) = ν/α, Ar (aspect ratio) = H/R, Hr (relative heater size) = D_H/D, where σ_T is the temperature coefficient of surface tension, ΔT the temperature difference between the heater and the chamber side wall, H the fluid depth, D the chamber diameter, R the radius, D_H the heater diameter, ν the fluid kinematic viscosity, μ the dynamic viscosity, and α the thermal diffusivity. For the onset of oscillations the surface deformation parameter S, which is defined as $S = \sigma_T \Delta T/\sigma$ (1/Pr), is also important. Also, in our concept of the oscillation mechanism the onset is delayed if the inertia forces associated with the flow become important or if the Reynolds number R_σ (= Ma/Pr) becomes large.

Both Ar and Hr were fixed at Ar = 2.0 and Hr = 0.1 in the OTFE. For each fluid the ranges of parameters covered in the tests were as follows. For 2 cSt fluid : Pr = 28 (at 25 °C), Ma < 8 x 10^5, S < 0.015. For 5 cSt fluid : Pr = 63 (at 25 °C), Ma < 6 x 10^5, S < 0.01. In our ground-based experiments (Kamotani et al., 1992) the flow was found to become oscillatory around Ma = 6.5×10^4 (for 4 mm dia. container) and S=0.007, so the values of both Ma and S in the OTFE exceed those values. In comparison, the parametric ranges of the STDCE were : Ma ≤ 3.1×10^5, S ≤ 0.0025, and 78 ≤ Pr ≤ 97. Therefore, the value of Ma exceeded Ma_{cr} but the parameter S was below the critical value in the STDCE.

III. RESULTS AND DISCUSSIONS

Total four tests were conducted as originally planned but the module for 5 cSt-3 cm was not used, instead the module for 2 cSt-1 cm was used twice for the reason explained below. All the tests were marred by bubbles generated in the fluid beyond a certain heater temperature and the flow was very much disturbed before the critical temperature was reached. Because of that the present experiment did not give us the critical temperature differences for the oscillations. Since the bubble problem was so serious, it is discussed first.

After filling the chamber with the fluid before each test the fluid looked bubble-free, except in the first test for 2 cSt-1 cm, and it remained so until the heater temperature reached a certain value. Until then the flow was steady and very axisymmetric. When the heater temperature, measured by the thermocouple touching the top of the heater, became around 60 -70 °C, a bubble was seen to form near the bottom of the heater and it became larger as time went on. Referring to Fig.1b the heater element was heated along its entire length including the part inside the ceramic bottom. Therefore, unlike the part exposed to the fluid where convection removed heat from the heater, the part in the bottom wall experienced much less heat transfer and consequently that part became much hotter. That situation itself did not give us a problem in our ground-based testing. However, for the space modules epoxy was used to seal the gap between the heater and the bottom wall (see Fig.1b). The epoxy was needed to stop fluid leakage through the gap during the pressure test for space qualification. It turned out that the epoxy generated vapor when it became very hot and in the absence of buoyancy the vapor bubble stayed near the epoxy and grew. The bubbles not only disturbed the flow field as they got bigger but they also created thermocapillary flow around them because of non-uniform temperature distributions over their interfaces with the fluid. For those reasons the flow field was very much altered. Attempts were made to remove the bubbles but they reappeared when the heater got hot and the test was halted. In our ground-based tests conducted after the space experiment the same bubble generation was observed over the epoxy surface around the same heater temperature as in the space tests, although the bubbles rose to the surface in one-g.

The flow visualization and temperature data were recorded on video tapes but so far we have not received all the tapes for the OTFE especially the flow visualization tapes. We also recorded the downlinked video, mainly the flow visualization data, at the POCC but the video did not cover all the tests. For that reason our analysis of those data is not yet complete.

Fig.3 shows the variation of the heater, side wall and fluid temperatures in the first test with the 2 cSt-1 cm module. The time is measured from the start of heating. Because the video camera was not properly positioned, the heater temperature could not be read in the first three minutes. The time of the vapor generation from the epoxy is indicated in the figure but in this test there were two small bubbles in the fluid even before that time. It seemed that they drifted into the test chamber through the fluid filling line shortly after the start of the test. Their size was about the heater diameter. Despite the presence of those two small bubbles the flow was very steady and nearly toroidal motion was observed over a large part of the test section until the epoxy vapor generation became noticeable, at which time the temperature difference ΔT was about 32 °C. After that the bubble attached to the bottom of the heater grew larger and around time $=18$ min. the bubble size became almost equal to the container radius and the flow became very three-dimensional. The test was stopped shortly thereafter.

The critical temperature difference measured in the ground-based test using the same module was 40 °C ($S_{cr}=0.007$), so the bubble generation in the space test began before that ΔT. As discussed above, the flow remained steady and the flow structure was nearly toroidal up to about $\Delta T=32$ °C, based on which one can say that the flow was not oscillatory even at Ma $=1.3\text{x}10^5$. That value of Ma was twice as large as the 'critical' Ma measured in the ground based tests.

Fig. 4 shows the variation of temperatures in the second test with the 2 cSt-3 cm module. In this test the heater power was increased faster than in the first test because we thought, at that time, that by doing so we could get into the oscillatory state before the bubble generation. However, the flow became very disturbed and three-dimensional by the bubble generation starting around $\Delta T = 35$ °C. Just when the bubble activity became noticeable, the heater temperature decreased noticeably as seen in Fig. 4 but the reason for that is not yet known. Unlike in the first test no bubbles were present before that time and the flow was very axisymmetric and toroidal. Therefore, one can conclude that no oscillations were observed up to Ma = 5.1×10^5 ($\Delta T = 35$ °C), which was 7.8 times larger than Ma_{cr} determined in our ground-based tests and $S_{cr} = 0.007$ (ΔT_{cr} = 40 °C) was not reached because of the bubble disturbances.

Much of the flow visualization and temperature tapes are not yet available for the third test with the 5 cSt-1 cm module. The bubble problem was worse in this test because the heater temperature was generally higher than in the tests with 2 cSt oil. The typical back-and-forth motion of particles associated with the oscillatory state was seen briefly but at present we do not know at what time and at what ΔT it appeared.

For the fourth test it was decided to repeat the 2 cSt-1 cm test rather than the originally scheduled 5 cSt-3 cm test because the bubble problem was expected to be worse in the latter case. Also we decided to heat up very slowly in this test to see whether it had any effect on the bubble generation. Fig. 5 shows the temperature variations during the test. The fluid was bubble-free and the flow was very axisymmetric until about $\Delta T = 30$ °C, at which point the bubble generation began to be noticeable. As in the second test, the heater temperature reading was unstable for some time after the bubble activity began. The size of bubbles grew with increasing temperature. When ΔT was about 38 °C the flow appeared to go through a sudden transition although the bubble activities did not show any sudden change at that point. After the transition the flow path changed and became three-dimensional. Although the transition occurred near $S_{cr} = 0.007$ ($\Delta T_{cr} = 40$ °C), whether the transition was related to oscillatory thermocapillary flow could not be determined .

CONCLUSIONS

Some conclusions from the present experiment are as follows.

1. Although steady thermocapillary flow was observed, the vapor bubbles generated by the epoxy fillet disturbed the flow before it became oscillatory so that the critical temperature differences were not determined. However, indications of oscillations were seen in some tests.

2. The flow remained steady even at Ma which was 7.8 times larger than the 'critical' Marangoni number determined in our ground-based tests, which shows that the Marangoni number is not the

appropriate parameter to describe the onset of oscillations.

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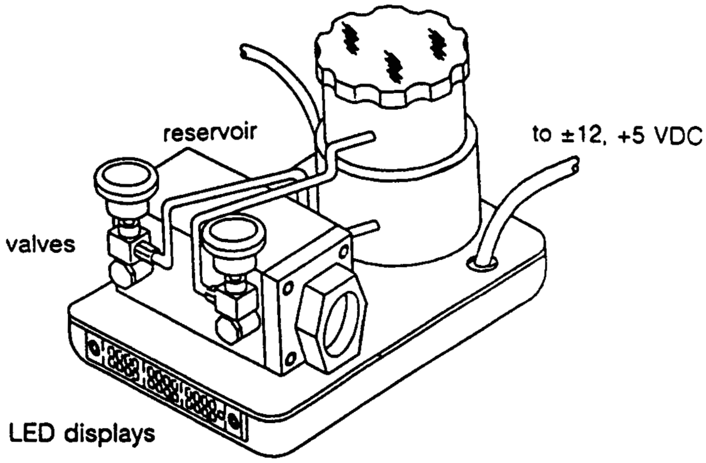
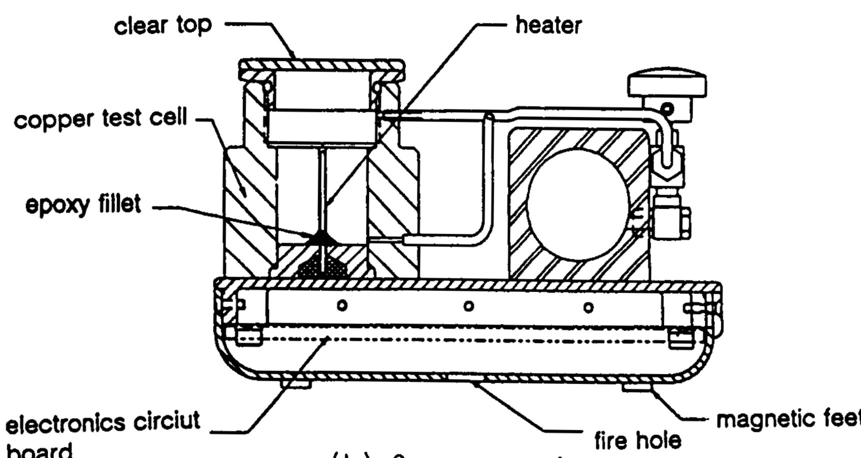


(a) Sketch of test module



(b) Cross-section

Figure 1 Sketch of test module for OTFE.

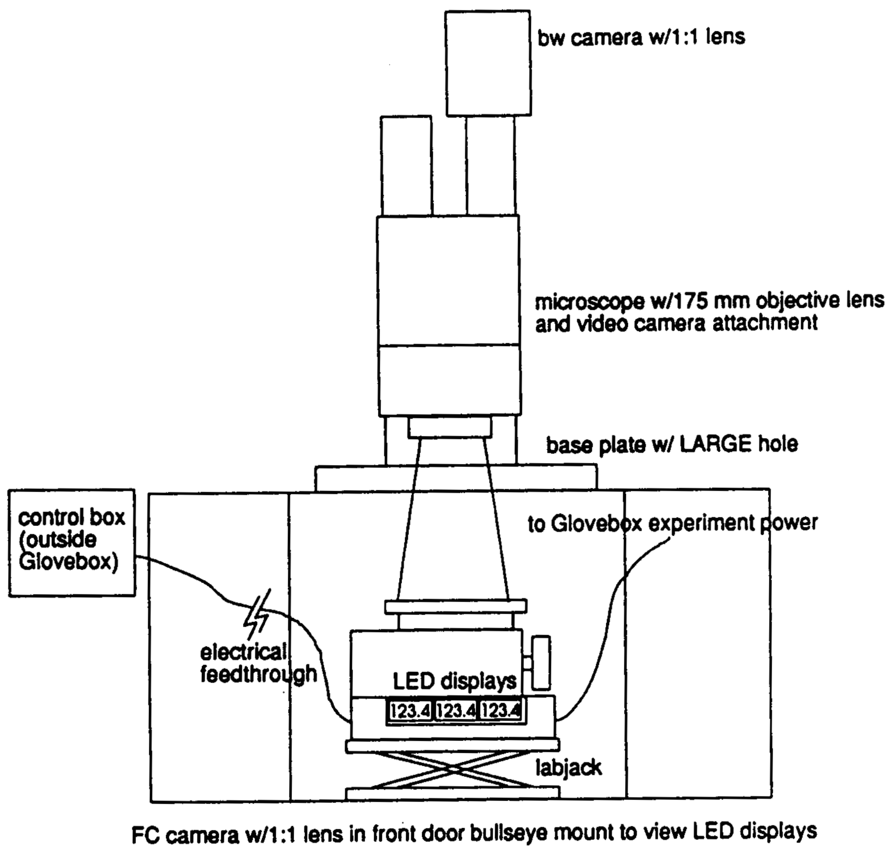


Figure 2 Experimental arrangement of OTFE.

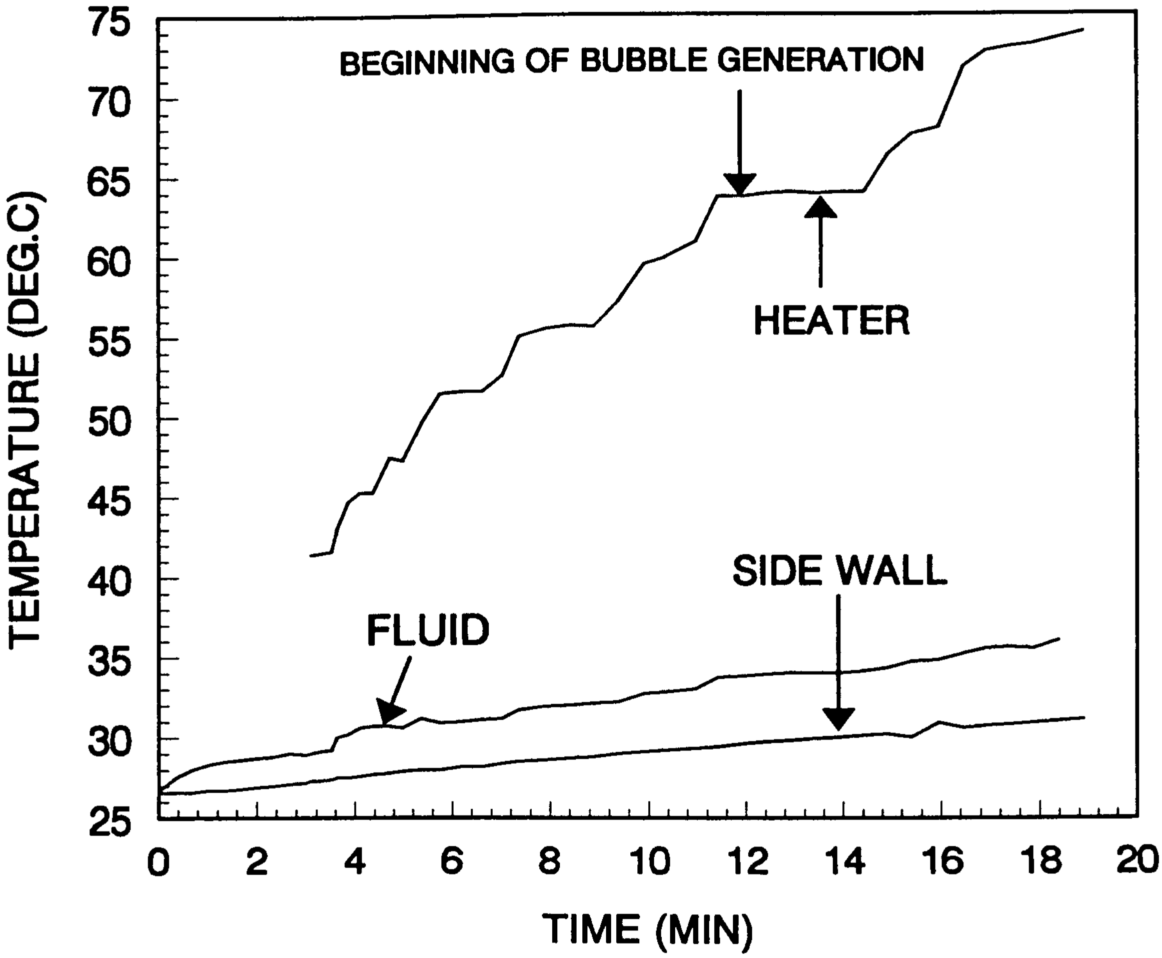


Figure 3 Temperature variations in Test 1 with 2 cSt-1 cm module.

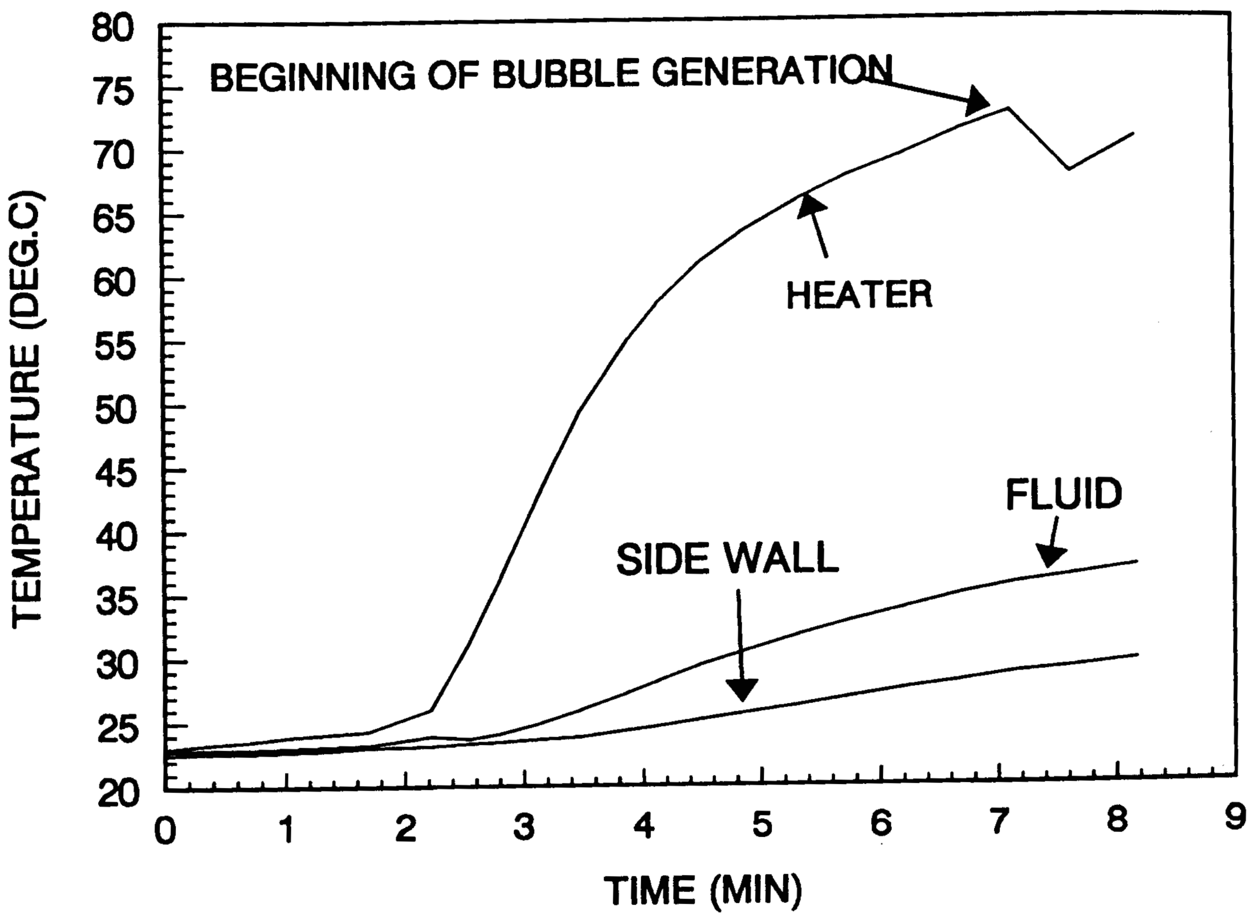


Figure 4 Temperature variations in Test 2 with 2 cSt-3 cm module.

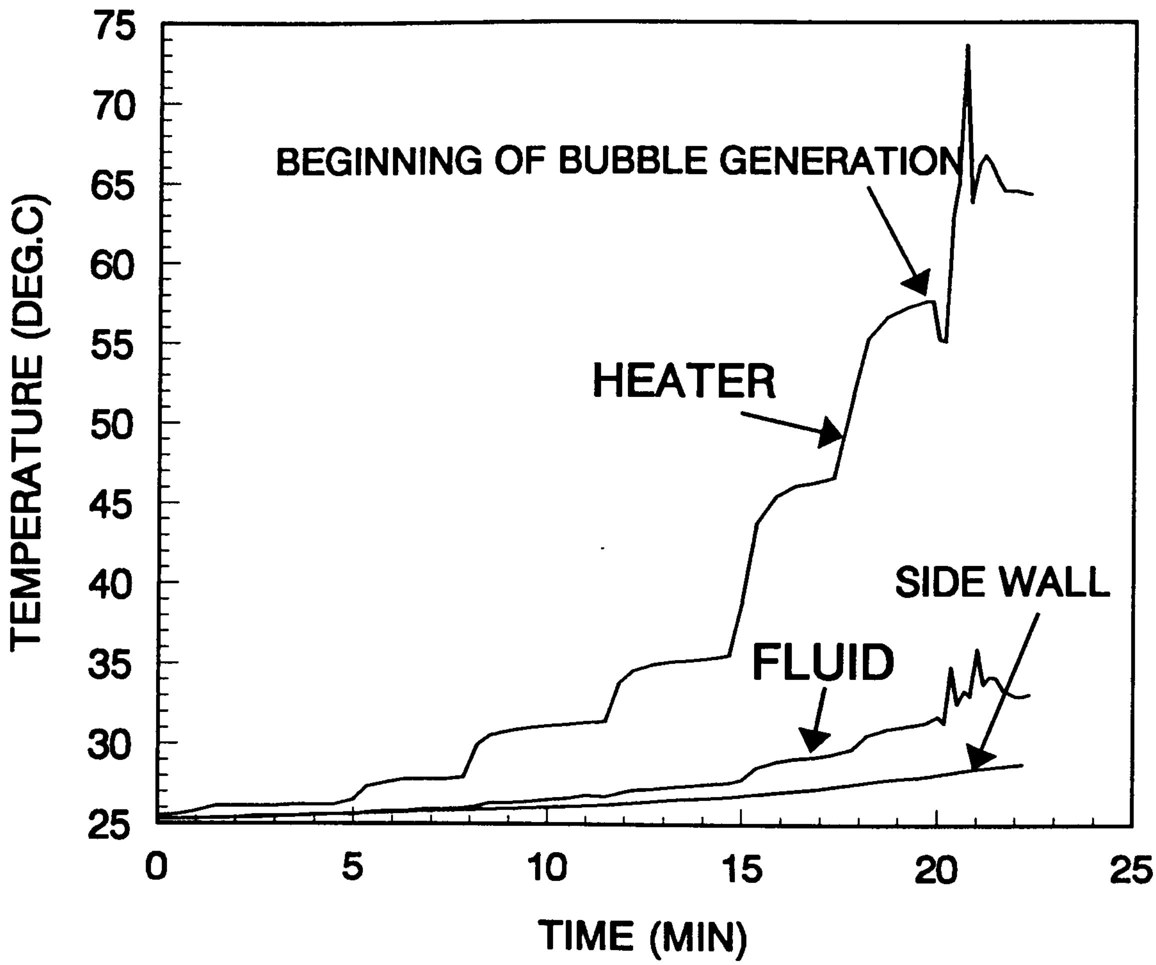


Figure 5 Temperature variations in Test 4 with 2 cSt-1 cm module.

Discussion
(Speaker: Y. Kamotani, CWRU)

Question: *On USML-2, what steps are being taken to circumvent the bubble problem ?*

Answer: Okay, to avoid the bubble problem; Now in 1g, the bottom wall is made of Teflon and the heater just goes through the gasket and there is no epoxy. That is supposed to be sufficient. According to our KC-135 flight results, no bubbles were created. So that is what we used in 1g, but for this experiment, we changed the design and paid the price. Also in STDCE-2, we follow the same parametric ranges and aspect ratio but in OTFE-2 we want to study the aspect ratio effect. We want to make it deeper.