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SURFACE TENSION DRIVEN CONVECTION EXPERIMENT-2 (STDCE-2)

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ABSTRACT

The Surface Tension Driven Convection Experiment-2 (STDCE-2) was conducted aboard the USML-2 Spacelab which was launched on October 20, 1995. The main objective of the experiments was to study oscillatory thermocapillary flows in microgravity. Thermocapillary flows were generated in cylindrical test chambers filled with 2 centistokes silicone oil. Six modules were used to study three different chamber diameters and two different heating modes. Tests with both flat and curved free surfaces were conducted. The flow field was studied by flow visualization and an infrared imaging system recorded the oil free-surface temperature. An optical (Ronchi) system was used to measure the oil free-surface deformation and motions. A total of 55 tests were conducted and oscillations were found in most of them. The data are currently being analyzed.

INTRODUCTION

Thermocapillary flow is known to become oscillatory under certain conditions. However, its cause and the dimensionless parameter(s) to characterize the onset of oscillations are not yet fully understood despite the fact that many investigators studied the phenomenon for many years. One major reason for the lack of understanding is that some of the available experimental data on oscillatory thermocapillary flows taken in one-g environments are confusing or contradictory because of buoyancy. For that reason we have conducted a series of thermocapillary flow experiments in microgravity.

The first experiments, called the Surface Tension Driven Convection Experiment (STDCE), were performed aboard the USML-1 Spacelab in 1992 and the results were reported by Kamotani et al. (refs.1 and 2). The experiments were mainly for steady thermocapillary flows. One important finding was that the flow did not become oscillatory despite the fact that its Marangoni number (Ma, to be defined later) was several times larger than the critical Ma for the onset of oscillations found in our one-g tests using smaller test chambers (refs. 3 and 4). Since Ma is the main dimensionless parameter representing the flow driving force in the absence of buoyancy, the results implied that there must be other factors to characterize the onset. Our past theoretical and experimental work suggested that the additional parameter is associated with the free surface deformation. Based on that concept we designed the second series of experiments in microgravity.

The second experiments, called the Surface Tension Driven Convection Experiment-2 (STDCE-2) were performed during the USML-2 mission in October-November, 1995. Oscillations were found in those experiments and the conditions for the onset of oscillations were investigated under various conditions. Since a large amount of data was gathered in the STDCE-2 their analysis is not yet complete.

DESCRIPTION OF STDCE-2

Apparatus

Cylindrical containers of 1.2, 2.0, and 3.0 cm diameters were used in the STDCE-2. 2 centistokes silicone oil was the test fluid. The test fluid was stored in a reservoir attached to each container. The oil was put into the container before each test through a small filling hole at the bottom of the container and withdrawn to the reservoir after the test. The side wall of each container was maintained at a uniform temperature by circulating cooling water around it. Two different heating modes were employed (see Fig. 1). A submerged heater system was used to study flows over a range of imposed temperature differences (called the constant temperature (CT) mode). The heater diameter was 10 % of the container diameter. In addition, a surface heating system (a CO_2 laser system) was employed to study flows generated by various heat fluxes distributed across the surface of oil (called the constant flux (CF) mode). The CO_2 laser beam was absorbed within 0.1 mm from the oil free surface. The laser beam diameter at the oil surface was adjustable.

The oil free surface shape was varied by adjusting the total volume of the oil in the container. The free surface shapes are shown in Fig. 1. In all cases the fluid free surface was anchored at the top edge of the container side wall. For that purpose the side wall had a sharp edge and was barrier-coated. In the CT mode there were three shapes (flat, shallow concave, and deep concave), while in the CF mode a convex shape was also studied. In the CF mode each shape is a part of a spherical surface but in the CT mode the shape is more complex because two orthogonal radii of curvature at any point on the surface are different.

The flow field was studied by flow visualization. 70 micron pliolite particles were added to the fluid and they were mixed uniformly in the reservoir before the filling by shaking the whole test module. A video camera recorded the motions of the particles from above the container. The experimental arrangement is sketched in Fig. 2.

An infrared scanner (IR imager) was used to measure the free surface temperature distribution. It operated in the wavelength range from 8 to 14 μm. Our ground based tests had shown that the technique was a very useful tool to study the thermocapillary oscillation phenomenon. The IR imager developed for the present experiments is described in detail by Pline et al. (ref. 5)

An optical method called Ronchi system was employed to measure the free surface deformations and motions. It was designed to measure the slope of the free surface up to 20 μm/mm, from which the surface shape was to be constructed after the flight. It was used only for flat free surface tests. Various types of grating were tried during the tests to find the optimum setting to measure a given oscillation pattern.

Three thermistors were placed along the length of each heater to monitor its temperature. One thermistor monitored the side wall temperature near its top edge and another thermistor recorded the air temperature above the oil surface. The fluid temperature was measured by a movable thermistor probe placed near the mid-radius of each container (see Fig. 1). Its bead diameter was 0.5 mm. Its vertical position was adjusted manually and placed close to the free surface usually. The effect of the probe on the oscillation phenomenon was investigated by comparing the data with the probe out and those with the probe completely withdrawn. The probe was also used to determine the position of the free surface.

In conjunction with the STDCE-2, a glovebox experiment called the Oscillatory Thermocapillary Flow Experiment-2 (OTFE-2) was conducted. The OTFE-2 experiments were performed only in the CT mode and the test chamber design was similar to the CT chambers in the STDCE-2. The flow visualization was the main diagnostic technique in the OTFE-2.

Parametric Ranges

The important dimensionless parameters for steady thermocapillary flow in the present configuration with flat free surface are: Ma (Marangoni number) = $\sigma_T \Delta T H/\mu\alpha$, 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 overall temperature variation along the fluid free surface, ν the fluid kinematic viscosity, μ the dynamic viscosity, α the thermal diffusivity, H the container depth, R container radius, D the container diameter, and D_H the heating zone diameter (the heater diameter in the CT mode). In the case of curved free surfaces the shape is specified by the relative total fluid volume (total fluid volume/total fluid volume for flat free surface).

Since Ma is the only parameter that contains ΔT (the driving force for the flow) in the above list, the conditions for the onset of oscillations should be specified by Ma for a given Ar, Hr, and Ar. However, in our earlier work we have shown that Ma is not sufficient to specify the onset conditions. One objective of the present experiments is to confirm that in the reduced gravity conditions of space. Our past work suggested that free surface deformation plays an important role in the oscillation mechanism. In that case a parameter such as capillary number (Ca = $\mu U_r/\sigma$, where U_r is the characteristic velocity scale of the flow and σ the surface tension) is also important. In fact, our first space experiments (STDCE) were designed based on Ma but no oscillations were found even though the range of Ma was much larger than the range of Ma where oscillations were found in our ground-based tests. Therefore, the STDCE-2 experiments had been designed based not on Ma but on our concept of the oscillation mechanism.

The test conditions in the STDCE-2 and OTFE-2 experiments are summarized in Table 1. In all, 55 tests were conducted (13 CT tests and 42 CF tests) in the STDCE-2, and 4 tests were performed in the OTFE-2.

Silicone oil with ν = 2 centistokes at 25 °C was the test fluid. In the temperature range of the STDCE-2 tests its Prandtl number varied from 18 to 28. The aspect ratio was unity in the baseline tests but in some additional tests in the CF mode Ar was changed to 0.5 by inserting a circular disk into the test cell to raise its bottom. Hr was fixed at 0.1 in the CT tests but varied from 0.05 to 0.4 in the CF tests. The range of Ma was Ma $< 5 \times 10^5$. In the OTFE-2 the container aspect ratio was set at 0.5 and 2.0 to study the effect of Ar on the onset of oscillations.

Operation of STDCE-2

One important feature of the STDCE-2 was that the tests were run interactively. All three video images (flow visualization, IR images, and Ronchi patterns) were downlinked simultaneously using the HIPAC system to the Payload Operation Command Center (POCC) at Huntsville, Alabama. We followed the tests at the POCC, communicated with the astronaut who was conducting the test, and helped him or her identify the onset of oscillations. The astronaut also followed the test from the start to the end and was very much involved in the experiments. The astronaut setup each test, filled the container, ramped the heating power up manually based on his or her flow observation, stopped the ramping whenever something interesting was observed, and changed the grating for the Ronchi system as the oscillation pattern changed. The data obtained in one test were analyzed by us immediately after the test and the test conditions for the subsequent test were determined and uplinked. This interactive operation was very useful and many interesting phenomena were found as a result.

PRELIMINARY RESULTS

All tests were completed successfully, with every test, except one, producing oscillatory flow. We conducted all of the pre-mission defined tests as well as several tests that were re-runs to establish repeatability. The quality of all the data (video and digital) was excellent. All of our onboard Hi-8 video tapes (about 120 tapes) and RAM memory cartridges (20) were used. We are still analyzing those tapes and data. We are also conducting numerical analysis of the flows to supplement the experimental information.

Preliminary analysis shows the following trends. (1) The critical temperature differences and heat fluxes for the onset of oscillations for the 1.2 cm chambers with flat free surfaces were close to those found in our ground-based tests. However, for the 2 and 3 cm chambers the critical values were much lower than those found on the ground, showing the effect of buoyancy in the latter. (2) The largest critical Marangoni number in the STDCE-2 tests was nearly three to four times larger than that found in our ground based-tests with using smaller chambers, which means that there is no fixed critical Marangoni number to specify the onset of oscillations. (3) The critical values increased as the free surface was made more concave. The critical values also increased when the chambers were made shallow.

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Table 1. Summary of STDCE-2 and OTFE-2 tests.

No. of CT tests with Ar = 1

DIA. (CM)	FLAT	S.C.	D.C.
1.2	2	2	1
2	2	2	1
3	1	1	1

Total 13 CT tests with Ar = 1

(S.C.=shallow concave surface, D.C.=deep concave surface, see Fig.1)

No. of CF tests with Ar = 1

CONTAINER DIA. (CM)	BEAM DIA. (CM)	FLAT	S.C.	D.C.	CONVEX
1.2	0.12	1	1	1	
	0.24	1	1	1	
	0.4	1			
	0.6		1	1	
2	0.1	1	1	1	1
	0.2	1	1	1	1
	0.4	1	1	1	1
	0.6				1
3	0.15	1	1	1	
	0.3	3	1		
	0.6	1	1	1	

Total 32 CF tests with Ar = 1

Additional 10 CF tests with Ar = 5

No. of OTFE tests (CT tests only)

DIA. (CM)	Ar=0.5	Ar=2
1.2	1	1
2	1	1

Total 4 OTFE tests

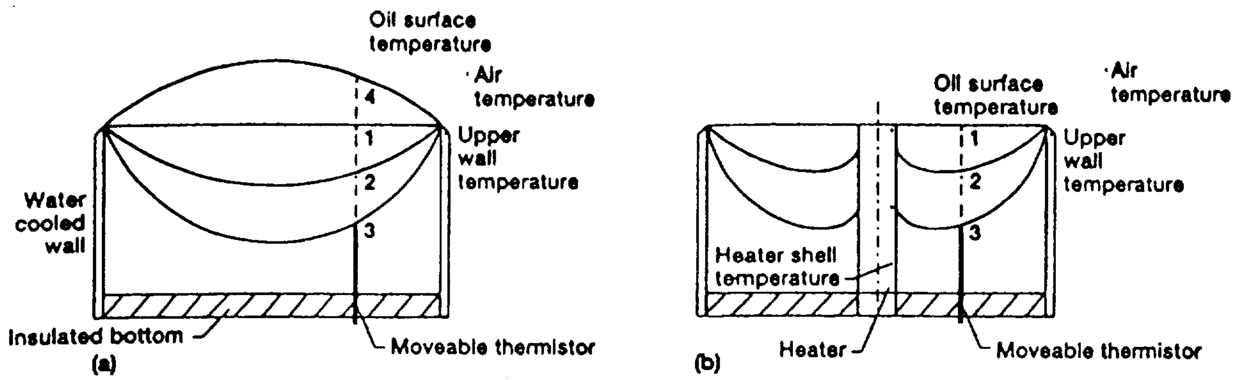

Figure 1. Free surface shapes in STDCE tests: (a) CF cells, (b) CT cells.

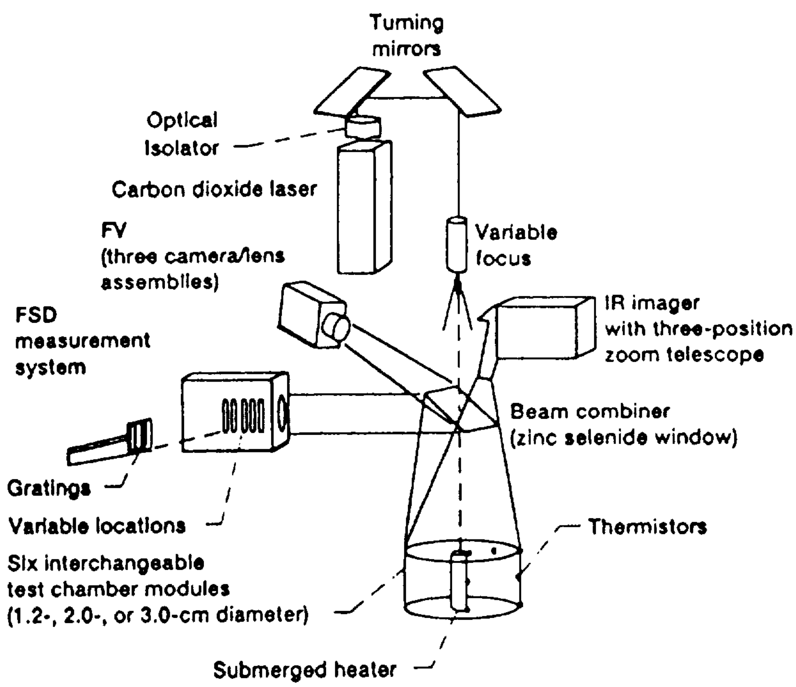

Figure 2. Test setup of STDCE.