SURFACE TENSION DRIVEN CONVECTION EXPERIMENT

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I. INTRODUCTION

Thermocapillary flow is driven by a thermally induced surface tension variation along a liquid free surface. In the earth-gravity environment such flows are usually overshadowed by buoyancy driven flows, but at reduced gravity conditions their influence could be significant ([1]). Among various types of flows that can occur at low-gravity thermocapillary flows are perhaps the most interesting not only scientifically but also because of their importance to such technological applications as the containerless processing of materials. Therefore with the advent of the microgravity sciences and applications program considerable attention began to be given to thermocapillary flows.

We at Case Western Reserve University started a comprehensive theoretical and experimental research program on the subject as early as 12 years ago and it is still being continued. Our past work as well as the work done by others is summarized in Chapter II. From those studies it became apparent that thermocapillary flows are very complex and that there are several serious limitations to the ground-based work. Therefore, experiments at low-gravity are needed in order to understand better such complex flows. The justification for low-gravity experiments is presented in Chapter III.

Our original design of a space experiment, which started about 10 years ago, was intended to demonstrate thermocapillary flow in a reduced-gravity environment. Since then the scope of the experiment has been expanded so that quantitative scientific tests will be performed in space. The Science Requirements Document (SRD) for the expanded experiment was issued in 1985 and was reviewed by the PACE science review board. To clarify aspects raised by the board the SRD was revised and accepted in June 1985 by the board. The Conceptual Design Review of the experiment was held in November, 1985 and because of the Challenger accident the board asked us to expand further the scope of the experiment to reflect decreased reflight possibilities. The current science requirements are based on this further expansion and are discussed in Chapter IV.

To obtain as much information as possible from the proposed experiments it is necessary to continue our ground-based research work especially on oscillaory thermocapillary flow. The support work is described in Chapter V.

II. PAST WORK ON THERMOCAPILLARY FLOW

Since several papers (e. g. [1-3]) discuss in detail the past work on thermocapillary flow and its importance in crystal growth, only the work pertinent to the proposed experiment is discussed herein.

Ostrach [2] derived by a formal procedure the important dimensionless parameters for thermocapillary flow including the effect of buoyancy. The work shows that in liquids other than liquid metals thermocapillarity is dominated by buoyancy in a normal gravity environment unless the system is made very small. Flat and rigid free surfaces were assumed in the work. The important parameters in reduced gravity with flat free surfaces are:

Marangoni number, $Ma = \partial\sigma/\partial T \;\; \Delta T H/\mu\alpha$

Prandtl number, $Pr = \nu/\alpha$

aspect ratio, $Ar = H/L$

where $\partial \alpha / \partial T$ is the variation of surface tension with temperature, ΔT the overall temperature variation along the free surface, μ the viscosity of the fluid, ν the kinematic viscosity, α the thermal diffusivity, and H and L are the depth and length of the fluid domain.

Because of difficulties in investigating thermocapillary flows experimentally over wide ranges of parameters in one-g the effects of the above parameters on the flows were studied mainly by numerical analyses. Clark and Wilcox [4] investigated thermocapillary flow in floating zone. They imposed fixed surface temperature distributions, thereby missing an important feature of the flow, namely, the coupling between the surface temperature distribution, which is directly related to the driving force of the flow, and the velocity field. Fu and Ostrach [5] were the first to study the coupling phenomenon over wide ranges of Ma, Pr, and Ar. It is shown in that work that with increasing Ma the surface temperature distribution tends to be relatively flat over a large part of the free surface and sharp temperature drops occur in small regions adjacent to the hot and cold ends, so the flow is mainly driven in those corner regions. Recent numerical analyses [6, 7] improved the numerical accuracy of Fu and Ostrach but their accuracy is still poor beyond about $Ma = 5 \times 10^4$ due to the existence of very thin corner regions.

Experimentally Ostrach and Pradhan [8] demonstrated the existence of thermocapillary flow in reduced gravity in drop tower tests. Chun and Wuest [9] and Schwabe et al. [10] studied thermocapillary flows in small floating zones. Those two groups also found a transition from steady to oscillatory convection ([11, 12]), which they claimed occurred beyond a critical Ma. Kamotani et al. [13] conducted an extensive experimental study on the effects of various parameters on the onset of oscillation and concluded that Ma is not the only parameter to determine the onset. They suggested that flexibility of the free surface could play an important role and thus the capillary number (Ca) should be an important dimensionless parameter for oscillation. The idea was supported by the experimental data, which indicated that the oscillations are a result of coupling among the free-surface temperature distribution, the velocity field, and the free-surface shape (return flow). Subsequently Lai et al. [14] confirmed the idea mainly by a physical and scaling argument. They showed that the oscillation originates in the corner regions and the surface flexibility is represented by the parameter $S = (1/Pr)\ (|\partial\sigma/\partial T|\Delta T/\sigma)$, which can be called a modified capillary number. The parameter is the ratio of the surface deformation time scale to the thermal-diffusion time scale in the corner regions. Based on the data taken in float-zones the oscillation occurs when Ma is above 10^4 and S is larger than about 1.4×10^{-3}. Napolitano et al. [15, 16] conducted experiments in space with large float-zones ($\sim$ 10 cm, Ma $\sim 5 \times 10^5$) but did not observe oscillations, probably because S was too small. Not much is known about oscillations in other configurations. Lee and Kamotani [17] used a small rectangular container (< 1 cm) and heated the fluid by a thin wire spun across the container in the middle. They observed oscillations but they were of a different type caused by a Kelvin-Helmhotz instability along the interface between the surface flow and the relatively quiescent bulk fluid, in other words, the fluid was thermally stratified.

Theoretically the effect of free surface deformation on thermocapillary flow has been investigated in the past. Sen and Davis [18] solved steady thin liquid-layer problems in a two dimensional slot including surface deformation under zero-gravity by asymtotic expansion and matching techniques. Strani et al. [19] also treated a similar problem both by asymptotic theory and numerical solution, in which the surface deformation was shown to have a negligible influence on the steady flow field structure in the ranges of parameters encountered in practice. Pimputkar and Ostrach [20] were the first to discuss the transient phenomena of thermocapillary flows in thin-liquid layers. A formal non-dimensionalization was made which indicated an explicit ordering of the equations so that ad hoc assumptions were unnecessary. The flows and surface shapes were determined numerically for a family of different imposed surface temperature distributions.

As for theoretical analysis of the oscillation phenomenon Smith and Davis [21, 22] studied the stability problems of two-dimensional thin liquid layers by using linear stability analysis. They considered separately two types of instabilities called surface modes and thermal modes but did not obtain a proper criterion for the prediction of oscillations as obtained in experiments. It should be noted that their analyses were for very thin liquid layers and the aforementioned coupling was not considered, so the instabilities studied by them are not really related to the oscillation phenomenon observed experimentally in the past.

III. RATIONALE FOR SPACE EXPERIMENT

Despite the past work reviewed above, there are some important unanswered questions about thermocapillary flow:

1. oscillation phenomenon - effects of configuration, surface thermal signature and heating mode
2. flow at large Ma ($> 10^5$) - thin corner regions, contact line behavior, subregions
3. flow in a low-gravity environment - effects of curved free surface at large Ma, g-jitter and free-surface deformability

The main reason why these subjects have not been investigated is that it is extremely difficult to study them in ground-based work due to the following problems.

Experimentally because of the effect of gravity on the free surface and that of buoyancy on the flow predominantly thermocapillary flow can be realized in one-g only in very small configurations (less than a few mm usually). As mentioned above, with liquid metals it is possible to generate thermocapillary flow in a relatively large configuration (~ 10 cm) but the dominant thermocapillarity is limited to the surface flow region only and also the static Bond number is large. Limited regions of thermocapillary flows can be obtained with other fluids when the free surfaces are heated from above to minimize natural convection. Considering the fact that the number of test fluids is limited because of the problem of surface contamination, a small configuration means a small Ma. It is possible to obtain only up to $Ma = 10^4$ in one-g but in actual crystal growth systems Ma can be up to 10^5 or above. Also with a small configuration it is difficult to investigate the flow in detail by quantitative measurements especially in the important corner regions. With increasing Ma the corner regions become thinner (their length scale relative to the geometric length scale is on the order of 1/Ma as discussed in ([23]), so normally small effects in the corners could become important. For example, the contact line behavior (dynamic wetting characteristics, wetting transition, wall corner shape and condition) could influence the flow. It is also possible that with the driving force concentrated in such small regions the flow develops subregions (cells) especially with a curved free surface. In one-g a curved free surface is possible only in a small configuration. The driving force for thermocapillary flow acts in the direction tangent to local free surface, so with a curved surface the driving force direction changes along the surface. This is quite different from the behavior with a flat surface in one-g.

As for numerical analysis of steady thermocapillary flow at large Ma, there are a few serious problems at present. First, to resolve the important corner regions we need a large computational power and an accurate numerical scheme especially with a highly curved free surface. Secondly not all the boundary conditions are well known. It is difficult to specify the contact line conditions accurately. The degree of surface contamination is also difficult to be specified. There is also a possibility that $\partial\sigma/\partial T$ is not the only parameter to describe the surface condition even when the surface is clean [24]. Therefore, as was done in the field of natural convection in the past, numerical work needs to be carefully guided by experiments before they yield meaningful and useful results. A numerical analysis helped design the proposed experiment and it will also complement the experimental data but it cannot replace the experiments.

So far observations of oscillatory thermocapillary flow have been limited to a simulated floating zone configuration in which a small liquid column is suspended vertically between differentially heated cylindrical metal rods. In that situation the free surface is vertical so that a strong surface flow can oppose directly the effect of buoyancy, which makes it easier to avoid thermal stratification. That configuration also makes it easier for the flow to oscillate by allowing azimuthal traveling of disturbances [11]. If we inhibit the traveling, the critical temperature difference increases substantially [13]. In other configurations with horizontal free surfaces the fluid layer tends to be thermally stratified unless the configurations are very small. The stratification gives rise to a Kelvin-Helmholtz type instability before the onset of oscillations associated with thermocapillary flow [17]. It thus seems that the effect of various configurations on the oscillation phenomenon can only be studied in reduced gravity conditions. In the floating zone configuration the heating mode is fixed (imposed temperature difference) and the thermal signatures are more or less independent of other parameters. The effects of heating mode and surface thermal signature can be studied in that configuration (as we are currently doing) but they need to be studied also in other configurations. Numerical analysis of the phenomenon is extremely difficult because, in addition to the problems associated with steady flow analysis discussed above, the flow is unsteady and it is necessary to incorporate the coupling among the free surface shape, the surface thermal signature, and the velocity field. We need to do more work on the subject and, at the same time, considerably more experimental information must be obtained in reduced gravity to guide the numerical work.

In a reduced gravity environment the dynamic behavior of a large free surface is different from that in one-g in that instead of gravity, surface tension controls the behavior. Thus, how the free surface deforms during oscillation cannot be studied accurately in one-g. Besides, the deformation is too small to be measured accurately in one-g. According to our previous study [25] the effect of g-jitter on the free surface motion is negligible as long as its level is kept less than 10^{-4}g. However, at large Ma even a small free surface motion near the contact lines could induce a large change in the flow structure for the reasons discussed above.

IV. DESCRIPTION OF SPACE EXPERIMENTS

Experiments on thermocapillary flow in reduced gravity have been proposed to study the following aspects:

1. the extent and nature of thermocapillary flows at large Ma($> 10^4$)
2. temperature distributions along the free surface and in the bulk fluid, and their effect on the flow fields
3. the effect of heating mode on the flows
4. the effect of the liquid free surface shape on the flows
5. the onset conditions and nature of oscillatory flows

The study of the oscillation phenomenon is expected to be a difficult one, so the experimental system to study it in detail requires preliminary information from space experiments and continued ground-based work. For this reason two experimental series are proposed to accomplish the above objectives: the first one in which the first four items in the above list will be studied and the second one in which the oscillations will be the main subject. Attempts will be made in the first experiment to make the flow oscillatory. Only the design and procedure of the first experiment are described herein. A more complete description is given in [26].

4.1 Experimental Design

In the proposed experiment a circular dish of 10 cm in diameter and 5 cm in depth will be used to hold the test fluid (Fig. 1). A circular geometry is chosen to make the flow axisymmetric to simplify the analysis and to maintain the axisymmetry even when the free surface is highly curved. A floating zone configuration is also an important one especially because the oscillation phenomenon has been studied in that geometry on the ground. However, the latter configuration is being studied in space by Napolitano et al. [15, 16] and it is not a convenient configuration to impose various surface heat fluxes. The dimension of the container is chosen for the convenience of flow observation. The test fluid will be 10 centistokes silicone oil ($Pr \approx 100$). It is safe and transparent, and it has been found to be reasonably insensitive to surface contamination. Its viscosity value gives the desired Ma range. The fluid will be heated in two ways as illustrated in Fig. 1. In one case the fluid will be heated by an outside heating source to impose fixed heat flux distributions along the free surface (called CF (constant heat flux) tests herein). In the other case a cylindrical heater (1 cm dia.) will be placed at the center of the container to impose fixed overall temperature differences along the free surface (CT (constant temperature) tests). In the CF tests both the heating zone diameter and the total heat flux will be varied while in the CT tests only the imposed temperature difference (ΔT) will be varied. At the present a CO_2 laser seems to be a good heating source in the CF tests because the heating area can be easily adjusted by a lens and it has been found to be absorbed readily by silicone oil (within about 0.2 cm depth). The side wall of the container will be cooled by forced liquid flow around it in order to maintain a uniform temperature over the side wall and to minimize the time to reach steady conditions. In most of the tests the free surfaces will be kept flat to simplify the analysis and measurement. In the tests with curved free surfaces the amounts of the fluid in the container will be adjusted to obtain the surface shapes shown in Fig. 2. The situation with 0 deg. apparent contact angle is avoided to maintain a well defined contact line position.

The flow field will be studied by flow visualization. Particles of order several microns will be mixed with the test fluid. A cross-section of the container will be illuminated by a laser sheet and the particle motions in the plane will be recorded by a sufficiently high resolution recording system (video system or movie camera). (Fig. 3). The temperature field will be studied by thermocouples (a thermistors) which will be placed at specified locations in the fluid. The surface temperature distribution will be measured by a scanning radiometer which will create an infrared image of the surface from which the surface temperature distribution will be determined. A numerical analysis of the flow will complement the measurements.

4.2 Experimental Procedure

Two heating modes (CF and CT experiments) will be studied. In the CF experiment a total of seven tests will be conducted with various total heat inputs and heating zone diameters. The conditions for those tests are summarized in Table 1. In one test the flow will be observed from the initial quiescent state to the final steady state to study the complete time history of the flow development, which is expected to take about one hour according to our numerical calculation. Other tests will be conducted successively with each test lasting 10 minutes, which is about the time for the velocity field to become nearly steady. The free surface will be curved in two tests. Because of the surface curvature the flow visualization and the surface temperature measurement are inaccurate in some regions especially near the control line, so we will investigate ways to correct the errors as much as possible.

A total of five tests will be conducted in the CT experiment with various values of ΔT and two free surface shapes as summarized in Table 2. Again one run is for complete flow development study.

In both CF and CT experiments the values of Ma and S are selected so that in some cases their values far exceed those critical values for the onset of oscillation in floating zones.

V. SUPPORTING GROUND-BASED WORK

To obtain as much useful information as possible from the space experiments three main subjects are being studied: the experimental techniques, the thermocapillary flow and oscillation phenomenon, and the numerical analysis.

5.1 Experimental Techniques

Some experimental techniques employed for the proposed experiments are being evaluated and calibrated.

In the thermography technique used to measure the free surface temperature it is important to relate what is measured to the surface temperature. The radiation detected by the instrument comes from a finite thickness layer below the surface, so if there is a large temperature variation within that layer, the measured temperature could be much different from the surface temperature. With the laser heating the temperature gradient tends to be very large near the surface, so the problem needs to be carefully assessed. The system is being calibrated using an arrangement identical to the proposed setup in conjunction with the numerical analysis.

The quality of information we can extract from the flow visualization technique depends on several factors. At present we are working on the resolution of the recording system. A movie camera is preferred over a video system because of its high image quality but the recording time of the former presents a problem and a real time transmission of the experimental data to the ground (if available) requires the latter.

When we study the oscillation phenomenon in the second space experiment, the free surface motion will be analyzed in detail. Since it is expected to be small, an accurate optical system to measure a small deflection needs to be developed.

5.2 Study of Thermocapillary Flow

At present it is very important that we learn more about the oscillation phenomenon under various conditions. Experimentally we are testing configurations, heating modes and fluids including a miniature model of the space experiment to see whether and when the flows become oscillatory by thermocapillarity. Theoretically we are trying to incorporate the flexibility of the free surface into a relatively simple thermocapillary flow model to see if it is possible thereby to obtain oscillatory flows.

The effect of the corner region on thermocapillary flow at high Ma is another important subject. In the analysis of the flow the contact line is mathematically singular and, moreover, a wetting transition could occur in the region, so if the flow becomes driven mainly in that region at high Ma, the analysis could be difficult. On the other hand, a very minute amount of contamination could nullify the corner region especially the cold corner region toward which the flow (and the surface contaminants, if present) is driven. The subject is being studied experimentally and numerically.

5.3 Numerical Analysis

The existing finite difference program used in our past studies of thermocapillary flows is being modified to analyze large Ma ($> 5 \times 10^4$) flow accurately. Smaller grid sizes and increased number of grids are required. The CRAY X-MP24 system at NASA Lewis will be used to speed up the computations.

As mentioned above, we are also developing numerical programs to study the oscillations and the effect of the corner regions. The former includes the flexibility of the free surface. In the latter program the effect of curved free surfaces is included because the corner region is expected to be very much influenced by the free surface shape.

REFERENCES

1. Ostrach, S., Annual Review of Fluid Mechanics, Vol. 14, 1982, 313-345.

2. Ostrach, S., Proc. Int. Conf. Physico Chemical Hydrodynamics (Levich Conference 1977) Advanced Publications, 1977.

3. Schwabe, D., PCH Physico Chemical Hydrodynamics, Vol. 2, No. 4, 1981, 263-280.

4. Clark, P. A. and Wilcox, W. R., J. Crystal Growth, Vol. 50, 1980, 461-469.

5. Fu, B-I. and Ostrach, S., Proc. 4th European Symposium on Materials Sciences under Microgravity, 1983, 239-245.

6. Zebib, A., Homsy, G. M. and Meiburg, E., Physics of Fluids, Vol. 28, 1985, 3467-3476.

7. Bergman, T. L. and Ramadhyani, S., Numerical Heat Transfer, Vol. 19, 1986, 441-451.

8. Ostrach, S. and Pradhan, A., AIAA J., Vol. 16, No. 5, 1978, 419-424.

9. Chun, Ch.-H. and Wuest, W., Acta Astronautica, Vol. 5, 1978, 681-606.

10. Schwabe, D., Scharmann, A., Preisser, F. and Oeder, R., J. Crystal Growth, Vol. 43, 1978, 305-312.

11. Chun, Ch.-H. and Wuest, W., Acta Astronautica, Vol. 6, 1979, 1073-1082.

12. Schwabe, D. and Scharmann, A., J. Crystal Growth, Vol. 46, 1979, 125-131.

13. Kamotani, Y., Ostrach, S. and Vargas, M., J. Crystal Growth, Vol. 66, 1984, 83-90.

14. Lai, C. L., Ostrach, S. and Kamotani, Y., Proc. 1985 U. S.-Japan Heat Trjansfer Joint Seminar, San Diego, 1985.

15. Napolitano, L. G., Monti, R. and Russo, G., Proc. 5th European Symposium on Material Sciences and Microgravity, 1984.

16. Napolitano, L. G., Monti, R. and Russo, G., Naturwissenschaften, 1986, 352-355.

17. Lee, K-J., M. S. Thesis, Case Western Reserve University, 1986.

18. Sen, A. K. and Davis, S. H., J. Fluid Mech., Vol 121, 1982, 163-186.

19. Strani, M., Riva, R. and Graziani, G., J. Fluid Mech., Vol. 130, 1983, 347-376.

20. Pimputkar, S. and Ostrach, S., Phys. Fluids, Vol. 23, 1980, 1281-1285.

21. Smith, M. K. and Davis, S. H., J. Fluid Mech., Vol. 132, 1983, 119-144.

22. Smith, M. K. and Davis, S. H., J. Fluid Mech., Vol. 132, 1983, 145-162.

23. Lai, C. L., Ph.D. Thesis, Case Western Reserve University, 1984.

24. Neuhaus, D., Naturwissenschaften, 1986, 348-349.

25. Ostrach, S. and Kamotani, Y., Science Requirements Document, 1985.

26. Kamotani, Y. and Ostrach, S., J. Thermophysics and Heat Transfer, Vol. 1, No. 1, 1987, 83-89.

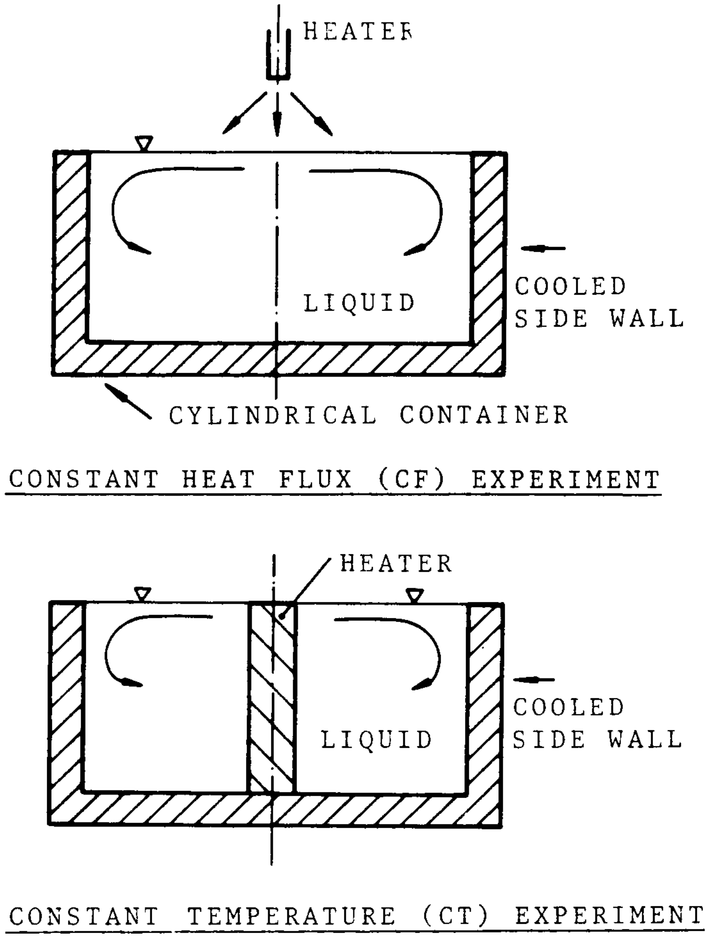

Fig. 1 Surface tension driven convection experiment

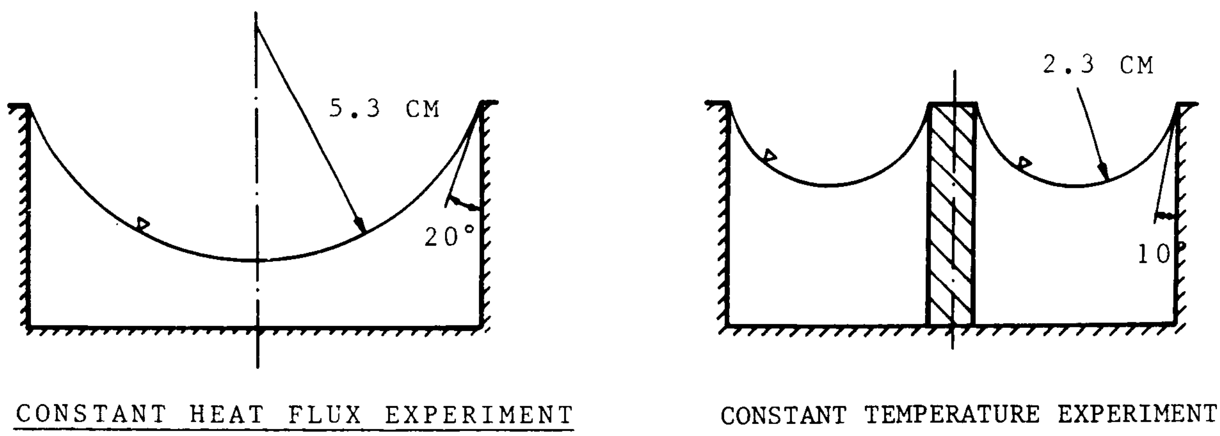

Fig. 2 Experiments with curved free surfaces

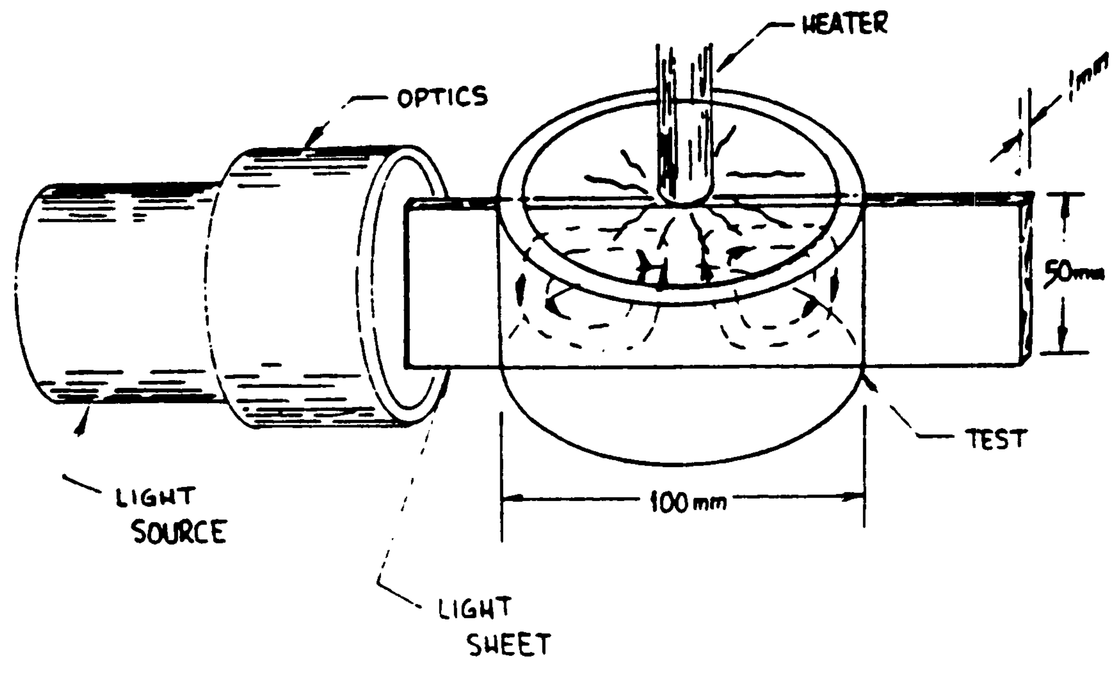

Fig. 3 Flow visualization system

Test No.	Heating Zone Dia. (mm)	Total Power (W)	ΔT (°C)	Ma	Free Surface Shape	Duration (min)
1	10	.5	10.4	4.2×10^4	flat	60
2	10	3.0	36.8	1.5×10^5	"	10
3	30	3.0	12.4	5.0×10^4	"	10
4	5	0.2	10.2	4.1×10^4	"	10
5	5	3.0	64.7	4.4×10^5	"	10
6	5	3.0	-	-	curved	10
7	30	3.0	-	-	"	10

The values of ΔT and Ma are computed by numerical analysis.

Table 1 Constant heat flux (CF) tests

Test No.	ΔT (°C)	Ma	Heater Power (W)	Free Surface Shape	Duration (min)
8	10	3.9×10^4	1.5	flat	60
9	25	1.2×10^5	6.8	"	10
10	60	4.1×10^5	32.8	"	10
11	≈ 10	3.2×10^4	1.5	curved	10
12	≈ 60	3.3×10^5	32.8	"	10

The values of heater power are computed by numerical analysis.

The values of ΔT for curved surface are estimates and Ma are based on average liquid depth.

Table 2 Constant temperatute (CT) tests