SURFACE TENSION DRIVEN CONVECTION

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In a normal gravitational environment, the free surface of a liquid in a container plays a passive role in the transport processes. However, at micro-gravity, the free surface can become the dominant factor. A simple but meaning-ful spaceflight experiment is proposed to investigate the nature and extent of flows induced by surface-tension gradients along the free surface. The in-fluences of container geometry, wetability, contamination, and imposed heating modes will be investigated.

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INTRODUCTION

At reduced gravity, surface-tension gradients on the free surface of liquids or molten metals become a dominant driving force for fluid flows. The nature and extent of such flows over ranges of conditions must be known both for the intrinsic scientific interest and for possible technological applications as, for example, in the containerless processing of the materials.

Theoretical analysis of such problems are extremely complex because the surface shape must be determined from the solution and the boundary conditions are not well defined. (The contact angle and its variation are not well known.) Furthermore, complete ground-based simulation is not possible because the interface shape and damping on earth are different from what they would be in a micro-gravity environment. Also, it is not possible to achieve the proper parametric ranges on earth. Thus, spaceflight experiments are required.

STATE OF EXISTING KNOWLEDGE

The distinction among physical mechanisms involved in such flows is unclear. For example, there exist two distinct basic modes of flow depending on whether the temperature and/or concentration gradients are along or normal to the free surface. Although this was indicated by Scriven (Proc. Internat'l Colloquim on Drops and Bubbles, Vol. 1, Caltech & TPL, Aug. 1974), the major emphasis has been placed on the latter configuration. Furthermore, the relevant dimensionless parameters are either incomplete or misunderstood. It is

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essential that these be explicitly known in order to make proper simplification of analyses, appropriate experimental simulations, the number of experiments minimal, and meaningful data correlations.

The existing analyses are based on ad hoc models in which there are inconsistent assumptions, the configurations are overly idealized and the boundary conditions are inappropriate in that surface shapes and temperatures are specified. Furthermore, the studies deal with restricted ranges of the parameters. Surface-tension gradient driven flows involve the solution of free-boundary problems, and therefore, the position and shape of the interface cannot be specified a priori but must emerge as part of the solution. Likewise, the surface-temperature distribution cannot be specified.

PROBLEM DESCRIPTION

The configuration to be studied is shown in Fig. 1. A liquid in a container will be subjected to a temperature variation along its free surface. Flow patterns, velocity and temperature profiles, free surface shapes, and transient phenomena will be observed and measured. The effects on those quantities of different heating modes (e.g., radiant or side wall), initial interface shape (contact angle), fluid properties, container shape, and liquid volume (aspect ratio) will be investigated.

PROGRAM BACKGROUND AND STRUCTURE

This experimental program was first proposed in 1974 to the Physics and Chemistry Experiments Working Group (PACE) where it was reviewed by a committee of scientists who strongly recommended such experiments. Funding for analytical and experimental justification of the program was given by OAST under the direction of PACE for 1975-76. A survey of the state of the art and some exploratory drop-tower experiments were made and that work received a peer review. In

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1977-79 feasibility studies were funded. During that period, theoretical modeling and analysis and laboratory tests were done.

RESULTS OF GROUND-BASED RESEARCH

Theoretical

Since no general and formal derivation of the relevant dimensionless parameters was available, such a derivation was made (Ref. 1 and 2). It was found that the flow depends on a surface-tension Reynolds number $R\sigma = \sigma_T \Delta Th/\mu\nu$, the relative effects of buoyancy to surface tension is given by a dynamic Bond number, $Bo = \rho\beta gL^2/\sigma_T$, and the transport depends on the Marangoni number, $Ma = PrR\sigma$ where σ_T is the change of surface tension with temperature, ΔT is the imposed temperature difference, h and L are characteristic lengths, μ and ν are the absolute and kinematic viscosities, respectively, ρ is the fluid density, β the volumetric expansion coefficient, g the acceleration of gravity, and Pr is the Prandtl number.

An analysis was made of the developing flow in a thin layer due to various imposed bell-shape surface temperature distributions. No ad hoc assumptions were made and the proper basic equations were obtained by formal ordering procedures. It was found that for a short time interval the free surface remains flat and the velocity monotonically approaches the Couette profile. Thereafter, the surface shape changes with time. The flow undergoes a development which results in a secondary cell and fluid recirculation. The nature and extent of such flows depend on the imposed surface temperature distribution. The results are given in Ref. 3.

An attempt was made in the laboratory to induce surface-tension driven flows in deep water layers by heating the surface from above so that a stabilizing temperature gradient would reduce buoyancy effects. This is contrary to
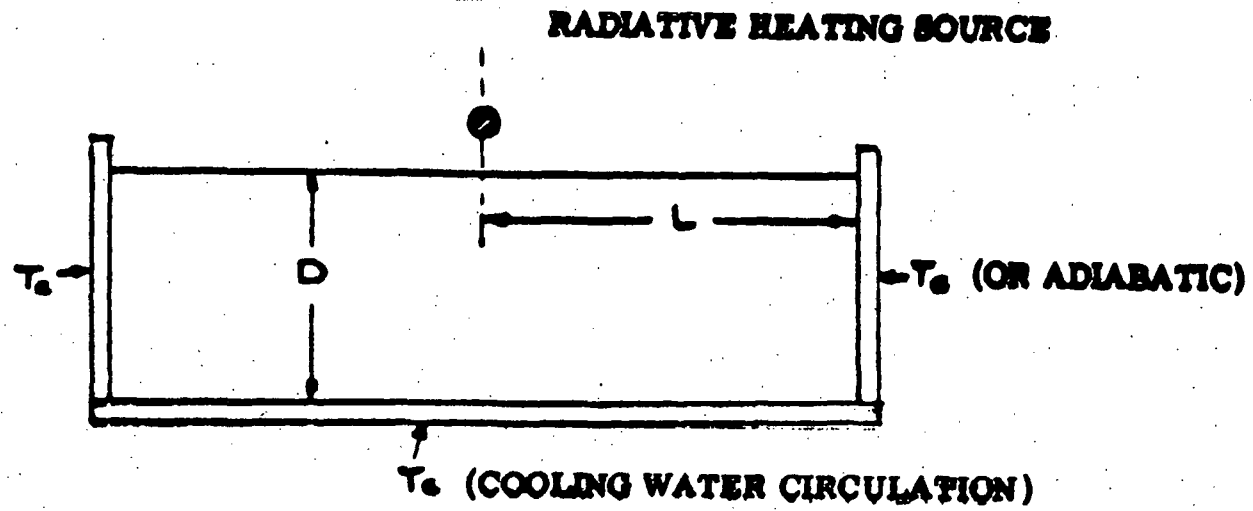
LABORATORY TEST APPARATUS

FIGURE 1

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the usual concept that such flows could only be achieved in thin layers. The test indicated that the new concept is valid but surface contamination obviated any quantitative data. Therefore, liquids other than water will be used in subsequent tests.

A series of tests was conducted in the NASA Lewis Research Center drop tower in which reduced-gravity conditions prevailed for about 5 seconds. The objectives of these tests were to generate flows driven by surface-tension gradients, to establish the time required for steady flow, and to obtain some qualitative measure of the flow. It was found that surface-tension gradients at micro-gravity cause measurable transient flows to occur. Surface velocities as large as 3 cm/sec were experimentally observed. The results of this phase of the research program are presented in Ref. 4.

SPACELAB RESEARCH PROGRAM OBJECTIVES

The experimental apparatus will be similar to that used in the laboratory and the schematic set-up is shown in Fig. 2. The aspects to be investigated in the spacecraft are:

(a) The extent and nature of the flows

(b) The effects of container material (wetability, contact angles)

(c) Configuration effects (circular and rectangular)

(d) Heating rate and distribution (surface or sidewalls)

(e) Effects of surface absorption on thermocapillary flows (contamination)

(f) Stability criteria (turbulence, secondary flows)

SPACELAB EXPERIMENT REQUIREMENTS

1. Measurements:

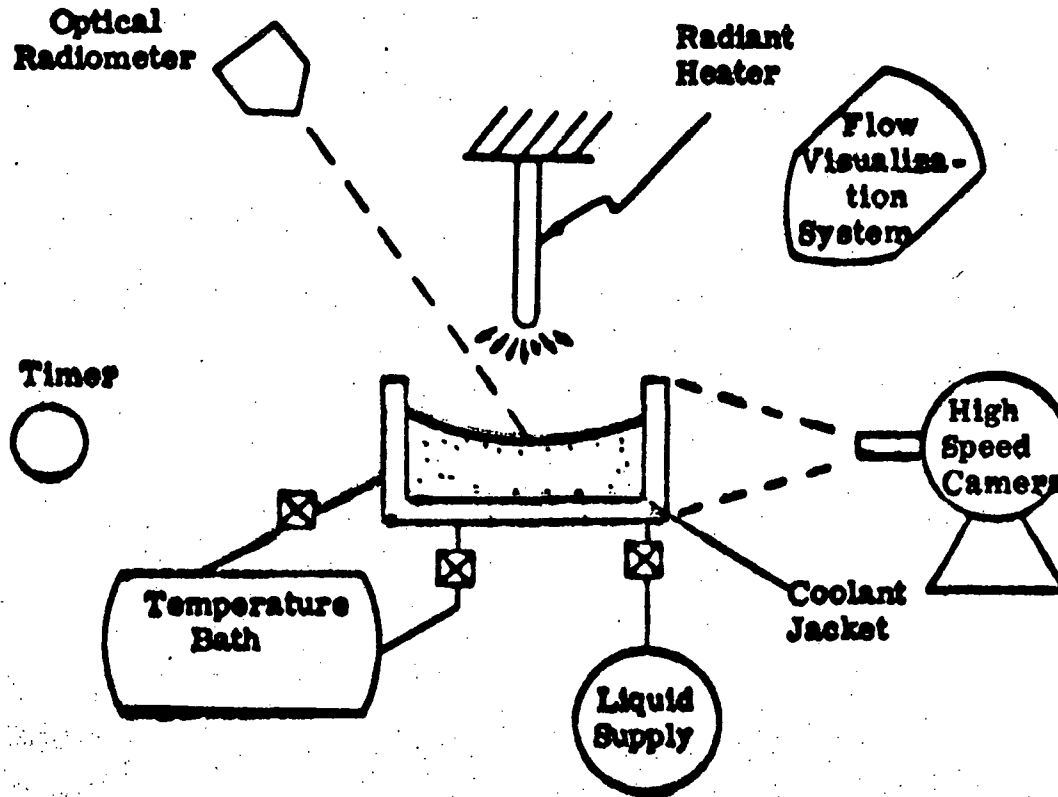Free-surface shapes

SPACELAB APPARATUS

FIGURE 2

Fluid velocity and flow visualization (accuracy $\pm$ 10%; velocity range 0-2 cm/sec)

Temperature (thermocouple accuracy $\pm$ 0.1°C, radiation thermometer accuracy $\pm$ 0.5°C)

2. Spacelab Support:

Environment (1 atm, 20°C)

Power (200w)

SUMMARY

The objectives of the research program are to determine the basic fluid mechanics and heat transfer phenomena of reduced-gravity surface-tension gradient driven convection. Analytical and experimental bases for this research have been established and considerable feasibility work has been conducted. The proposed experiment is simple to conduct and the measurement techniques are essentially state of the art.

REFERENCES

(1) Ostrach, S., Motion Induced by Capillarity, Physicochemical Hydrodynamics, Advance Publications Ltd., Vol. 1, 1977.

(2) Ostrach, S., Convection Due to Surface Tension Gradients, Proc. COSPAR Space Research, Vol. VIII, Innsbruck, Austria, 1978.

(3) Pimputkar, S. M. and Ostrach, S., Transient Thermocapillary Flow in Thin Liquid Layers, Presented at the 31st Meeting of the American Physical Society, 1978 (to be published in Physics of Fluids).

(4) Ostrach, S. and Pradhan, A., Surface-Tension Induced Convection at Reduced Gravity, AIAA Jour., Vol. 16, No. 5, May 1978.