N91-21341

CONTAINERLESS EXPERIMENTS IN FLUID PHYSICS IN MICROGRAVITY

E. H. TRINH
JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY

INTRODUCTION

The basic favorable conditions for low gravity studies of fluid physics are the removal of the overwhelming influence of sedimentation and of natural convective effects. If these conditions are combined with the elimination of the unwanted interaction of free-liquid surfaces with solids, such as those found in the sample containers, then experimental studies of unfettered capillarity-dominated phenomena become possible. The removal of the complicated and material-specific boundary conditions made possible by the containerless environment also renders the analysis of these phenomena more tractable and, therefore, allows the verification of theories and models that have long been the only means to advance our understanding of these areas of fluid physics.

This more beneficial environment will, however, not guarantee the successful performance of rigorous experiments if the appropriate instrumentation and physical parameter measurement and control are not available to the microgravity experimenter. Because the magnitudes of the forces and perturbations are small, tighter control of environmental influences such as the residual acceleration background, the thermal distribution field, the material species concentration distribution, and other extraneous effects introduced by the noncontact sample positioning fields must be exercised. On the other hand, one of the major advantages of the microgravity environment is the inherent ability to reduce the effects of the positioning fields to a very low level, and thus to significantly decrease their perturbing effects. Novel non-invasive sample and environmental properties measurement techniques must also be developed and implemented specifically for the on-orbit environment, and they should not add further perturbation to the sample.

The areas of interest in microgravity fluid physics cover multiple disciplines and are relevant to a variety of environmental conditions, from the more benign, ambient manned surroundings to conditions of ultra-high temperature and high pressure or vacuum. Basic study of the behavior of freely suspended liquids in gas or vacuum environments that are free from the Earth's gravitational field is a new area of investigation, and the methodology involved has not yet been completely mastered and understood. It, therefore, would be logical to develop the experiment concepts and instrumentation to carry out studies in more controlled and well-characterized conditions prior to attempts to access more restricted and adverse environments at ultra-high temperature. The ambient environment studies will serve to verify models that could then be applied in any environment. Of course different instrumentation and measurement techniques will be required to accommodate different environmental conditions, but the basic physical phenomena dominated by thermocapillary interactions will be described by the same models.

Some of the possible areas of research in microgravity containerless fluid physics studies will be suggested below. The current work carried out by researchers both in 1 G and in low gravity will then be described. Applications of the results of these low gravity studies to the basic understanding of the dynamics of free-liquid surfaces, of the transport processes involved in phase transitions, and of the properties of metastable liquids will also be discussed.

POSSIBLE AREAS OF INVESTIGATION

The fundamental physical system available for investigation is a free liquid in spherical or near-spherical shape under the predominant influence of capillary forces. The thermal environment is ideally uniform but can be varied in a controlled manner to create surface tension gradients or to uniformally elevate the sample temperature. Noncontact positioning techniques using acoustic, electrostatic, electromagnetic, or aerodynamic forces allow the controlled manipulation of the specimen: static deformation, solid body and differential rotation, driven and free shape oscillations can all be induced as desired. The remote positioning of the specimen also allows it to be largely decoupled from residual acceleration transients specific to the microgravity environment. A variety of processing environments that are specific to the desired investigation can be accommodated with controlled gas additions or partial evacuation or variation of humidity levels. The totally free-liquid surface can thus respond to any external stimulus in a manner characteristic of its surface properties: the natural response of a fluid sphere is then accessible to experimental examination, and the effects of controlled addition of surface adulterants can be specifically measured. In addition, partial contact with specific, well-characterized solid surfaces can be achieved to provide specific measurement of liquid-solid interaction in the absence of gravity.

Containerless experimentation is an additional opportunity for scientific study and offers a new approach to heterogeneous nucleation investigation by allowing the virtual removal of external contact sources that could serve as a basis for initiating an unwanted phase transition. This additional delay of the nucleation of a new phase will allow access to the metastable regions of the liquid state and the subsequent experimental measurements of their physical properties.

A. The Dynamics of Oscillating and Rotating Free Drops

Perfect sphericity of a liquid sample can only be achieved through the undisturbed influence of surface tension; this condition can be very closely approximated if the Earth's gravitational field effects are drastically reduced and if the residual influence of sample positioning forces is negligible. In practice, noncontacting stress fields are needed to probe the response of the drop-to-perturbation and to manipulate it. The vibrational dynamics of free drops can then be studied in both the linear small amplitude region as well as in the nonlinear regime. The transition from the ordered to the chaotic behavior of this simple mechanical system is thus accessible to controlled experimentation. The static and dynamics of uniformally and differentially rotating drops can be investigated in detail.

In addition to simple drops, compound liquid-liquid and gas-liquid combinations are of fundamental interest both in terms of basic physical reasons as well as for the various technological applications based on such systems. The removal of gravitational body forces allows experimental access to ideal geometries with perfect symmetry and concentricity amenable to theoretical analysis.

The behavior of both Newtonian and non-Newtonian liquids can be investigated using the same experimental capabilities at room temperature or at slightly elevated temperature. Physical parameters such as surface tension and density can easily be determined if the appropriate controls are provided.

Current ground-based and flight investigations are being carried out both theoretically and experimentally. Some of the areas covered are listed below.

* R. Brown at MIT has been analytically and numerically analyzing the static and dynamic shapes of free drops and has predicted the stability limits of the equilibrium shapes of rotating drops in gyrostatic equilibrium (1). In addition, the nonlinear large amplitude shape oscillation regime

has also been extensively investigated for both electrically charged and uncharged drops (2). Nonlinear characteristics that are indicative of chaotic behavior in the shape oscillations of free drops have been uncovered (3).

* Experimental investigations have been carried out at the Jet Propulsion Laboratory, Yale, and, subsequently, at Vanderbilt University (4–6). Ground-based experiments in immiscible liquid media using ultrasonic radiation pressure have investigated the linear and nonlinear regimes of free drop shape oscillations. The rotational behavior of simple and compound levitated drops are under current scrutiny in preparation to a space flight experiment. T. Wang performed microgravity experiments during the flight of Spacelab 3 in 1985. In addition to demonstrating the viability of acoustic containerless positioning techniques in space, he has obtained intriguing results on the shapes of rotating drops that have raised further questions about the influence of dynamic phenomena on these shapes (7). A refinement and extension of these experiments will be carried out during the USML-1 Spacelab flight in 1992.

B. Mass and Heat Transport Phenomena

The direct three-dimensional interfacing of a liquid surface to a gaseous or vacuum environment also allows the simplification of analytical studies of heat and mass transfer problems in the spherical or near-spherical geometry. Control of the liquid surface properties, the composition, pressure, and temperature of the environment coupled with the drastic reduction of uncontrolled natural convection will allow experimental access to a much wider parameter space. Small transfer coefficients can be measured, and the effect of forced convection can be experimentally decoupled.

Ground-based experiments using acoustically levitated droplets have been carried out at the Naval Research Laboratory, Battelle (Frankfurt) laboratory, and at the Jet Propulsion Laboratory to measure the liquid evaporation rate (8,9). The interference of the high intensity acoustic field and of the resulting forced convective flows cannot be eliminated in experiments carried out in 1 G. These investigations have concentrated, therefore, on the overall mass transfer rate or on the technological feasibility of accurately controlling the levitated drop volume. A team of researchers from the NASA Lewis Research Center and the University of Michigan are currently investigating the feasibility of a controlled drop evaporation experiment paying particular attention to the induced convective flow inside the freely suspended drop in microgravity (10).

C. Surface Rheology and Thermocapillary Phenomena

Containerless experimentation should allow the control of the liquid free surface composition either by postponing the contamination onset or by deliberately altering its properties by the addition of various surfactant. Time-dependent or steady-state mechanical and transport properties can then be experimentally investigated through various noncontact techniques. The verification of simpler theoretical models dealing with the properties of surface elasticity and viscosity will become possible with microgravity experiments.

Non-uniform thermal distributions on the drop surface can be generated, and the resulting thermocapillary phenomena can be observed and measured inside transparent droplets. Marangoni-flow phenomena can then be investigated in the absence of other body forces or external convective flows in microgravity.

* Current and past ground-based studies of the surfactant effects on the surface tension and viscosity of droplets levitated in an immiscible liquid medium have been carried out at Yale

University. An anomalous time dependence of both these parameters has been discovered. Preparations for a flight experiment in 1992 are being made (11).

* S. Subramanian at Clarkson University has carried out both theoretical and experimental studies of the thermocapillary flow generated due to a surface tension gradient on a free drop surface. Applications to the control of bubble motion within a melt in a containerless situation and in low gravity have been a driving motivation (12).

D. Measurement of Thermophysical Properties

Nonperturbing, remote measurement techniques based on containerless positioning techniques as well as other optical or spectroscopic methods should be made available in order to fully exploit the possibilities raised by the microgravity containerless experimentation program. Thermophysical properties currently being emphasized are density, surface tension, viscosity, specific heat, thermal diffusivity, and absolute temperature. Room temperature and elevated temperature measurements are required depending upon the materials or processes of interest.

* Investigators at the Jet Propulsion Laboratory have developed and validated techniques to measure the surface tension, density, viscosity, and index of refraction of levitated liquid specimens (13). Both room temperature and higher temperature experiments in microgravity are planned for the USML-1 flight to determine the accuracy of these methods in space.

* Other researchers at MIT and in Europe are planning to measure surface tension and viscosity of high-temperature metallic melts (between 1,000 and 1,700°C) using the same techniques (14). Flight experiments are planned for the IML-2 mission scheduled for 1993.

E. Undercooling, Nucleation, and Solidification Studies

The postponement of liquid to solid-phase transformation can be facilitated by containerless processing liquid samples. This postponement can easily be attributed to the removal of obvious heterogeneous nucleation of container surfaces. Although other factors such as suspended impurities and "dynamic" effects are still obstacles to the homogeneous nucleation limit, containerless experimentation widens the parameter space open to experimental investigation of the metastable (undercooled and superheated) liquid state. Controlled experiments in microgravity or even in 1 G will also allow detailed examination of the various factors responsible for the premature nucleation of the solid phase from the undercooled melt.

* Ground-based levitation undercooling of ordinary liquids, low melting metals and alloys have been obtained using ultrasonic and electromagnetic levitation (15,16), and drop tube studies have allowed quite significant undercooling of millimeter-size refractory metal alloys (17). Both 1 G and flight experiments are either being carried out or being planned for a future Spacelab flight of a containerless processing instrument.

* Containerless solidification from melts and from solution has been under scrutiny in ground-based laboratories for some time. High-temperature solidification velocities in metal alloys have been measured from electromagnetically levitated melts (18). Preliminary measurements of surface dendritic growth velocity at near-ambient temperature has been obtained for slightly undercooled Succinonitrile, and measurements at higher undercooling are being carried out at the present time (19). Flight experiments are also being planned for the IML-2 Spacelab mission by European investigators.

CONCLUSION

The physical phenomena associated with the behavior of liquid samples freely suspended in low gravity must be thoroughly understood prior to undertaking detailed scientific studies of the materials under scrutiny. The characteristics of molten specimens under the action of containerless positioning stresses must be identified and separated from the specific phenomena relating to the absence of an overwhelming gravitational field. The strategy designed to optimize the scientific return of reliable experimental data from infrequent microgravity investigations should include the gradual and logical phasing of more sophisticated studies building on the accumulated results from previous flight experiments. Lower temperature fluid physics experiments using model materials can provide a great deal of information that can be useful in analyzing the behavior of high temperature melts. The phasing of the experimental capabilities should, therefore, also include a gradual build-up of more intricate and specialized diagnostic instrumentation and environmental control and monitoring capabilities. Basic physical investigations should also be distinguished from specific materials technology issues. The latter investigations require very specific high temperature (and high vacuum) devices that must be thoroughly mastered on the ground prior to implementing them in space.

ACKNOWLEDGEMENTS

The support required for the writing of this paper and for the performance of some of the research described therein was provided at the Jet Propulsion Laboratory, California Institute of Technology under contract to the National Aerospace and Aeronautics Administration.

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Figure 1

Comparison between theoretical predictions on the nonlinear characteristics of the fundamental mode of uncharged simple drop shape oscillations. Numerical results predict an increasing percentage of the oscillation period spent in the prolate shape as the oscillation amplitude increases. This was confirmed by experimental results. Theoretical results predicting of a soft nonlinearity for large amplitude drop shape oscillations are also in agreement with experimental data.
Data of J. Tsamopoulos and R. Brown, J. Fluid Mech. 127, 519 (1983).

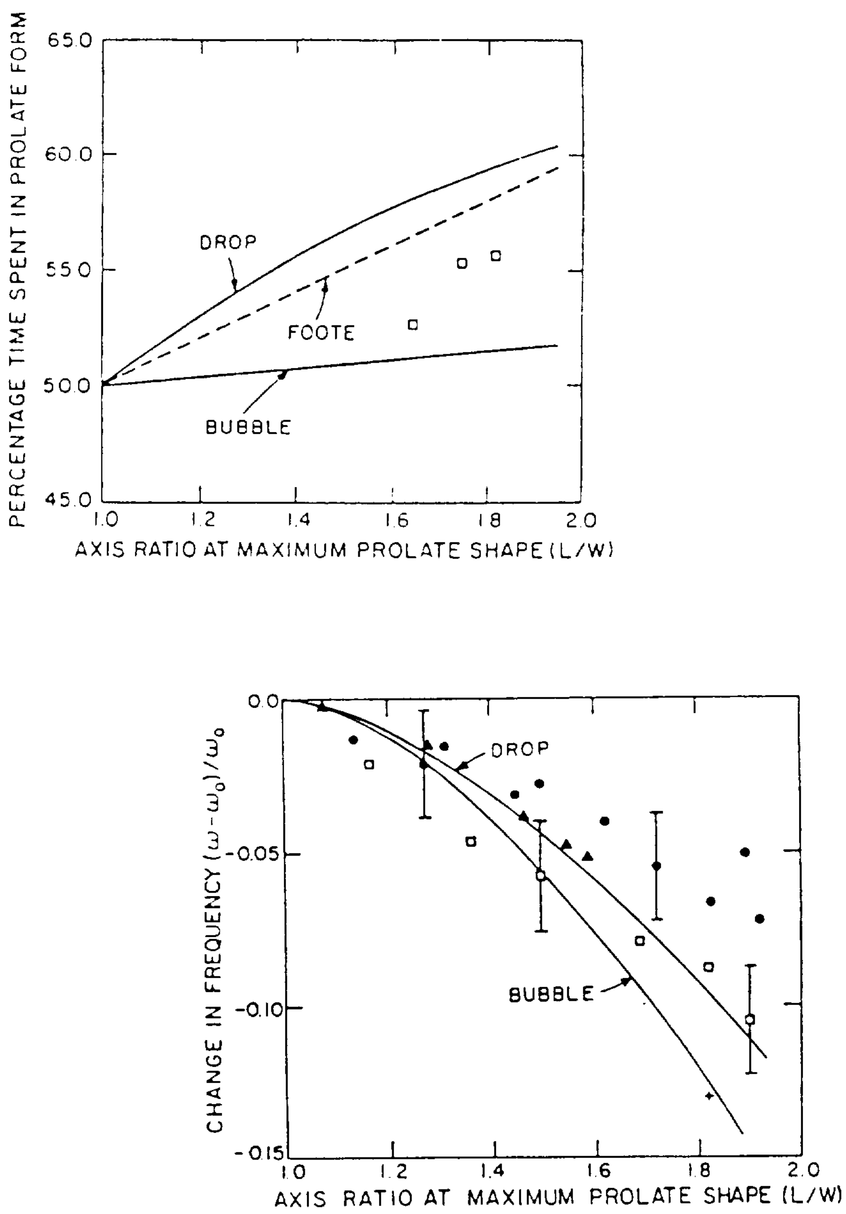

Figure 2
Results from space experiment carried out during the Spacelab 3 flight. The observed equilibrium shape of an acoustically rotated freely suspended drop of an aqueous solution of glycerin deviates from the predicted behavior at the point of transition between the axisymmetric and two-lobed shape (bifurcation). Dynamic, surfactant, and differential flows could be at the origin of this intriguing result.
Data of T. Wang, E. Trinh, A. Croonquist, and D. Elleman, Phys. Rev. Letters <u>56</u>, 452 (1986)

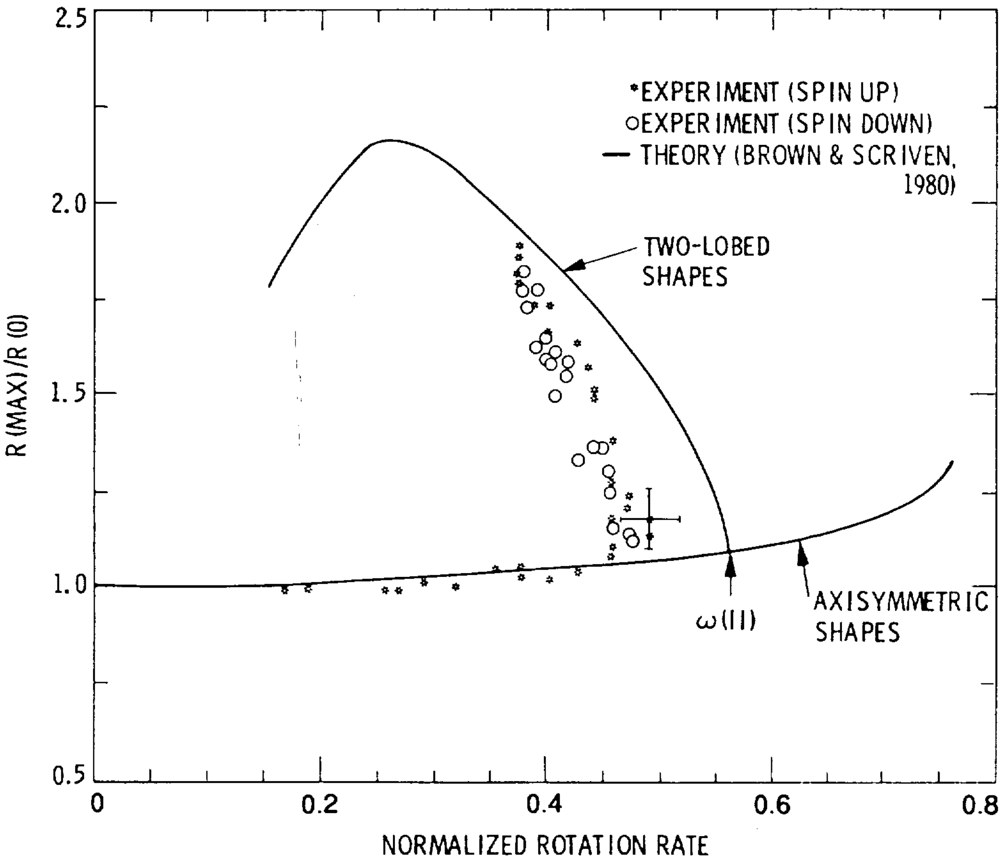

Figure 3
Tracer particles-based visualization of the internal flow of a freely suspended drop undergoing large amplitude drop shape oscillations. Steady convective flows have been observed in addition to the oscillatory motion.
Data from E. Trinh and T. Wang, J. Fluid Mech. 122, 315 (1982)

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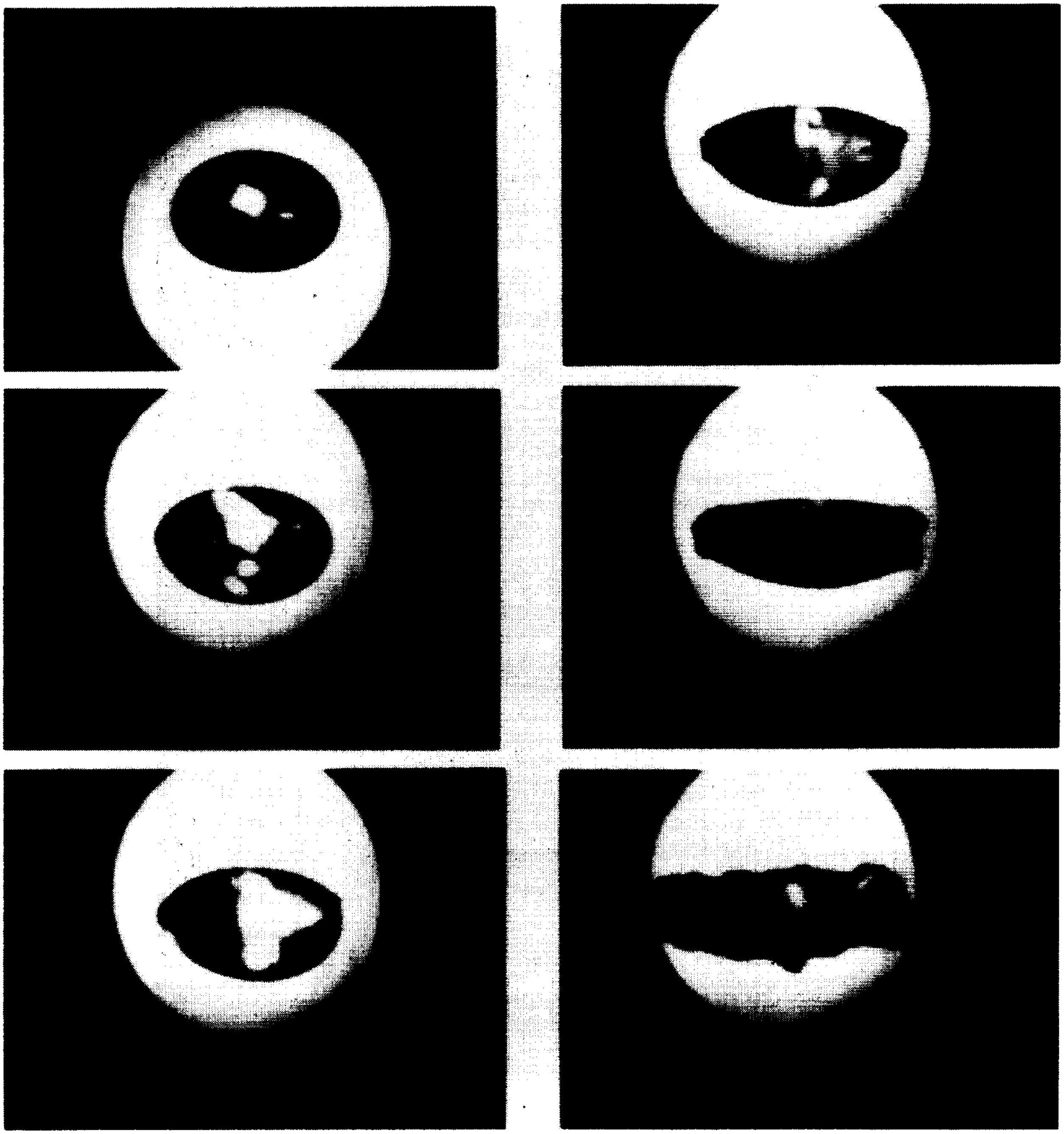

Figure 4
Containerless crystallization of levitated initially undercooled O-Terphenyl sample in 1 G.
Data from E.H. Trinh, Jet Propulsion Laboratory

Figure 5
Hypothesis regarding evaporation mechanism for a freely suspended liquid drop under diffusion-controlled regime and under convective flow.
From A.T. Chai and J.C. Duh, ESA publication SP 295, 492 (1990)

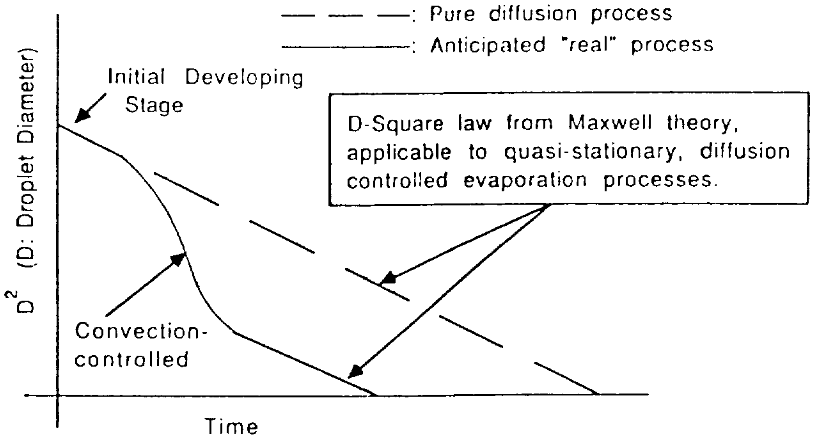

Figure 6
Theoretically predicted Marangoni flow patterns in a freely suspended spherical drop under a non-axisymmetric themal gradient.
From H.F. Bauer and W. Eidel, Acta Astronautica 15, 275 (1987)

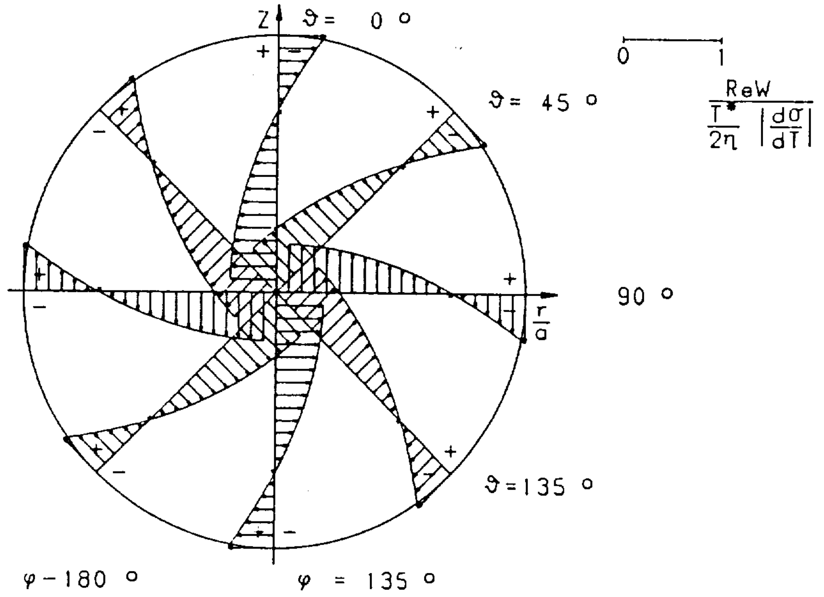

Fig. 2(g)

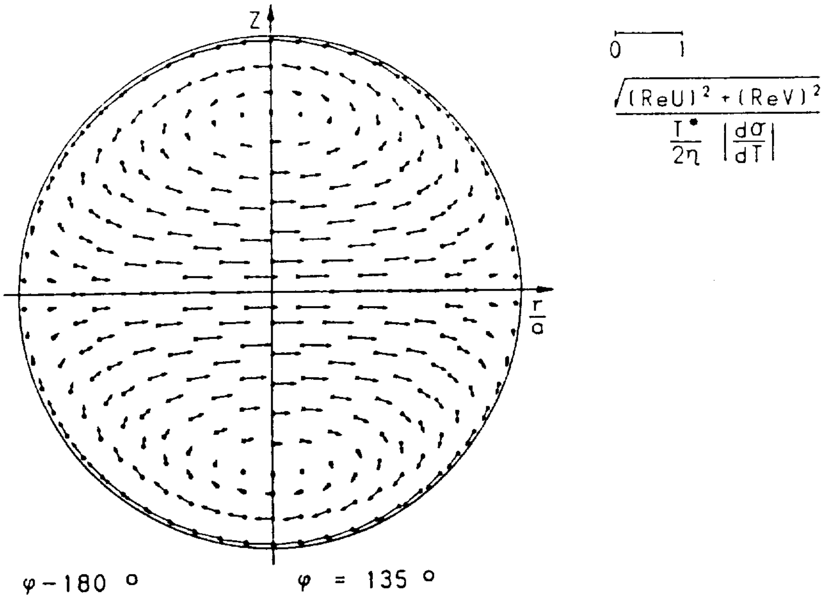

Figure 7
Equilibrium shapes of acoustically rotated charged drops under levitation in an electrostatic field.
From W.K. Rhim, S.K. Chung, and D. Elleman, AIP Conference Proceedings 197, 91 (1988)

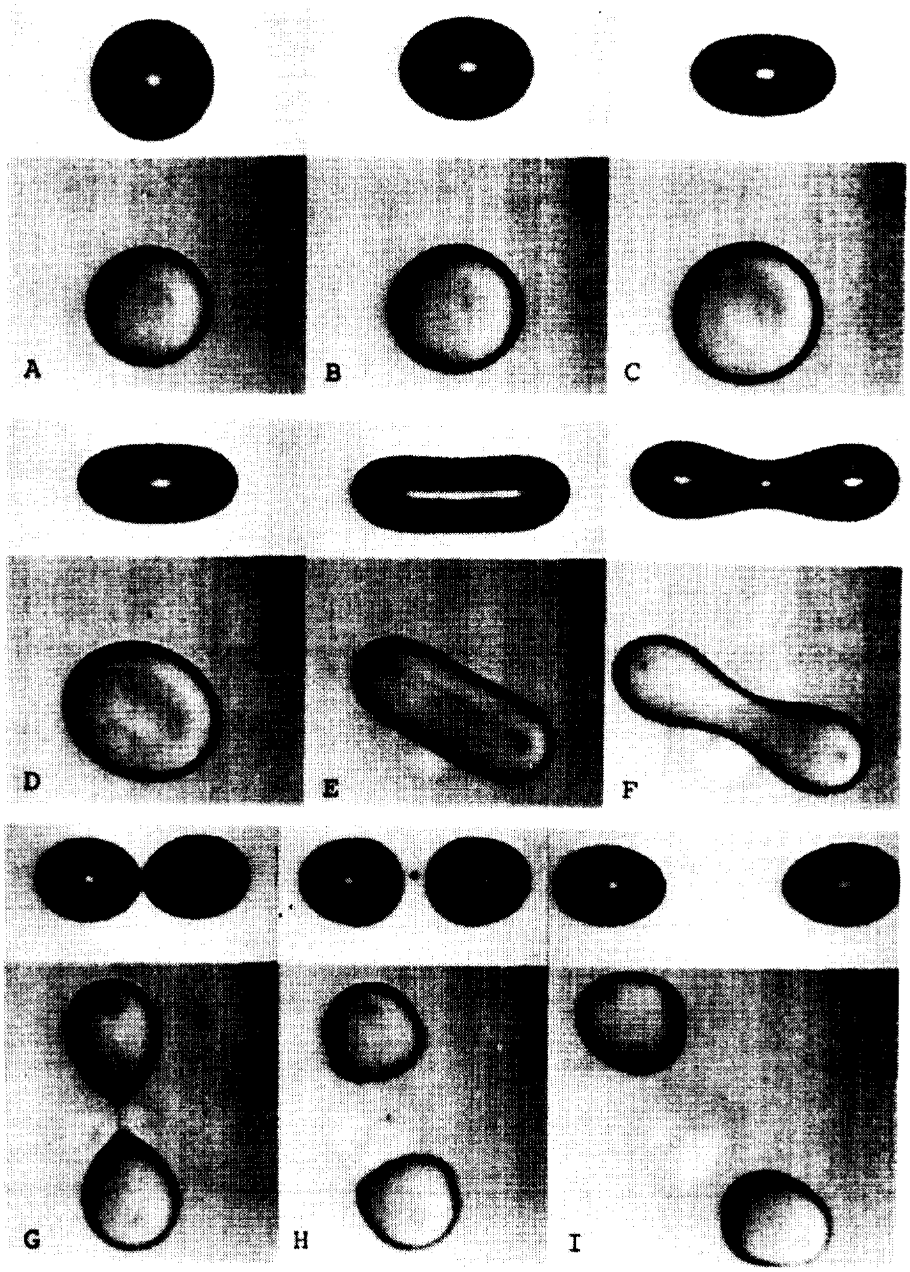

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Figure 8
Time history of the frequency and damping constant for a Hexane drop of approximately 1 mm in diameter in water at 22 C. The solid curves are theoretical predictions.
From H. Lu, "Study of interfacial dynamics of drops in the presence of surfactants or contaminants", PhD Thesis, Yale University 1988.