Interdisciplinary Transport Phenomena in the Space Sciences

Edited by S. S. Sadhal

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Participants of the Interdisciplinary Transport Phenomena IV Conference, Tomar, Portugal, August 2005.

Preface

Interdisciplinary Transport Phenomena in the Space Sciences

The future of scientific research in many fields lies in interdisciplinary activities, and "transport phenomena" is undoubtedly a broad area that forms a common thread covering various aspects of thermodynamics, fluid mechanics, and biological and materials sciences. With the aim of furthering interdisciplinary research in these areas with application to the space sciences, we are continuing with this very successful series of conferences in which we hope to share our ideas for healthy new research programs. Since interdisciplinary research is taking directions that require a vast base of knowledge and expertise, further progress demands that we share our individual expertise across traditional scientific boundaries, identify new arenas of scientific work, and initiate projects based on our collective knowledge and experience.

Transport phenomena continue to be a fundamentally important subject matter, encompassing a large range of disciplines, holding wide-open scientific challenges toward which we may be able to contribute. Nevertheless, progress in dealing with such challenges requires the active assembly of dedicated individuals willing to interact with each other and encouraging the propagation of new and unorthodox ideas. The future strength of science indeed lies in our willingness to adapt to these new challenges through scientific interdependence as well as the promotion of interdisciplinary activity. The present conference series on transport phenomena is indeed designed to provide the forums for the free flow of ideas and the stimulation of provocative discussions that may very well lead to a better understanding of the scientific principles that apply to cross-disciplinary research.

The conference organizing committee is grateful to various members of the scientific committee who have provided valuable help in getting this conference organized. We express our sincere appreciation to Professor Frank Schmidt, whose support in the capacity of the technical liaison for Engineering Conferences International (ECI) has led to the necessary endorsement from the ECI since the inception of this conference series. Thanks are also due to Eugene Trinh and Bradley Carpenter (NASA) as well as Alfonso Ortega (US National Science Foundation) for financial support from the respective U.S. government agencies. The staff at ECI in Brooklyn, under the leadership of Barbara Hickernell and Kevin Korpics, have done an enormous amount of organizational work, for which we are indeed grateful.

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Our gratitude also goes to all of the participants who have expended a great deal of time and effort in putting together high-quality scientific papers as well as participating in the peer-review process. We indeed appreciate the effort of Linda Mehta for working with the New York Academy of Sciences to give us the privilege of publishing the conference papers in archival form in the *Annals* after peer review. Thanks are also due to the entire publication staff for carefully typesetting this volume, and to Justine Cullinan for her painstaking proofreading.

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INTERDISCIPLINARY TRANSPORT PHENOMENA IN THE SPACE SCIENCES

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This volume is the result of a conference entitled **Interdisciplinary Transport Phenomena in Microgravity and Space Sciences IV**, held August 7–12, 2005, in Tomar, Portugal.

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Effect of Convection on the Measurement of Thermophysical Properties Using Levitated Droplets

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ABSTRACT: This article discusses the recirculating convection in free droplets levitated by either the electromagnetic forces or the electrostatic forces, and its effect on the measurement of thermophysical properties. In an electromagnetically levitated droplet, strong internal flow results from the vortical Lorentz forces induced by the surrounding coils. These forces are also responsible for free surface deformation. In an electrostatically levitated droplet, however, internal convection originates from the thermal gradient and the electrostatic forces are responsible for surface deformation only. Mathematical models for predicting the convection in these droplets and the surface deformations caused by either the electromagnetic or electrostatic forces are discussed. Results show that internal convection, when present, can have a significant effect on the measured data for the purpose of determining the thermophysical properties. The deformed surface assumes essentially the same oval shape in microgravity for both electromagnetically and electrostatically levitated drops. The deformation mechanism, however, is different. Future research directions in this area are also discussed.

KEYWORDS: Electromagnetic levitation; electrostatic levitation; magnetically driven flows; convection; turbulent flows; oscillation; finite element/boundary element modeling; free surface deformation

INTRODUCTION

Electromagnetic levitation and electrostatic levitation are two important containerless devices for microgravity applications. Levitation eliminates the use of a container for melts and hence enjoys freedom from contamination from the container walls. This advantage makes levitated droplets uniquely suitable for measuring the thermophysical properties of high melting point and corrosive materials. The properties that can be measured using the levitated

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droplets include heat capacity, surface tension, thermal conductivity, electrical conductivity, and viscosity.[1–7]

NOMENCLATURE

a_l	laser beam radius
A	magnetic vector potential
$\mathbf{B}$	magnetic field
C_p	heat capacity
$\mathbf{D}$	displacement current
$\mathbf{E}$	electric field
E_z	z-component of the electric field
$\mathbf{H}$	magnetic intensity
H	curvature
I_o	laser beam intensity
$\mathbf{J}, \mathbf{J}_i, \mathbf{J}_e$	current, impressed and induced currents
J_s	surface current density
k	system parameter
$\mathbf{n}$	outward normal vector
r_l	radial distance from the center of laser beam
$\mathbf{t}$	tangential vector
$\mathbf{u}$	velocity
p	pressure
Q, Q_c	electrical charge, critical charge
T	temperature
t	time
ϵ	emmisivity
η	viscosity
κ	thermal conductivity
χ	surface coordinates
Ω_1, Ω_2	domain of a droplet, free space
γ	surface tension
Φ	electric potential
σ	surface charge density
σ_s	Stefan-Boltzmann constant
$\bar{\sigma}$	stress

Electromagnetic levitation is based on Faraday's induction law for electrically conducting materials. By induction, the Lorentz force is generated in a conducting specimen when placed in an external AC magnetic field and the force is able to counterbalance the gravitational force if the external field is strong enough. Accompanying the levitation phenomenon are the Joule heating and eventually melting that result from the self-interaction of the induced currents. For a liquid sample, internal convection occurs inevitably due to the vortical nature of the Lorentz force field. The liquid sample also deforms in order to balance the force along the surface.

The concept of electromagnetic levitation is exploited to position a sample in microgravity to prevent it from drifting in space. In the absence of gravity, a larger sample can be achieved much more easily with a small applied field. Space flights with electromagnetically positioned droplets have been made and experiments have been successfully conducted to measure various material properties, such as heat capacity, surface tension, thermal conductivity, electrical conductivity, and viscosity of melts that would be otherwise difficult under normal gravity. One interesting idea to measure surface tension and viscosity is to squeeze a droplet at its equator by applying a strong force there and subsequently releasing the force to cause the droplet to undergo free oscillation. From the transient oscillation frequency and amplitude decaying, the surface tension and viscosity data can be obtained, respectively. This idea is rather easily realized under microgravity by an appropriate design of a dipole coil, which may also be used for induction melting. A critical prerequisite for an accurate measurement, however, is that the internal convection, driven by the electromagnetic forces, must be carefully controlled.[8–12]

Electrostatic levitation is another containerless process that is now widely used for microgravity research. It is developed based on the principle of electrostatics. In essence, a positively charged particle placed in an upward electric field experiences a lifting Coulomb force resulting from the interaction between the charges and the external field. If the force is sufficiently strong, it can counterbalance the gravity and support the sample in air. An important issue is that only a very small sample can be supported under normal gravity because of the Rayleigh limit on the amount of charges on a liquid sample, above which the sample disintegrates. A microgravity environment eliminates this drawback, enabling a sample of an adequate size to be positioned electrostatically.

Electrostatic levitators are perceived to have some attractive advantages over electromagnetic levitators. One of them is that an electrostatic field in principle can levitate any types of materials including metals, semiconductors, and insulators, while electromagnetic levitators are limited to electrical conductors only. Also, for electrically conducting samples levitated in vacuum, no electrically driven convection occurs because the electric field inside the droplet is constant.[13–15] This is in direct contrast with electromagnetic levitation, where strong stirring is inevitable. In reality, however, internal convection in an electrostatically levitated droplet may come from other sources. Thus, the issue of convection also needs to be addressed for an accurate measurement of thermophysical properties using electrostatically levitated droplets.

Considerable research has been carried out to develop a systematic understanding of the transport phenomena associated with the droplets in the TEMPUS device and the electrostatic levitators.[16–47] It is now well established that strong stirring in electromagnetically levitated droplets stems from the vertical component of the Lorentz forces, while the temperature gradient is mainly responsible for recirculating melt flows in electrostatically levitated droplets.[16–41] This internal convection complicates the analyses of the experimental measurements and is the culprit for the contamination of the measured data for thermophysical properties. It is thus desirable for these applications that the convective flow is either eliminated or controlled below the rate of transport by molecular diffusion. Because of the limited experimental techniques for directly measuring the internal flows, computational modeling provides an indispensable tool to assess the effect of convection and to provide rational guidelines for designing and/or interpreting space-based experiments on thermophysical property measurements.

This article discusses the convective flows and transport phenomena in both electromagnetic and electrostatic levitators and their effects on thermophysical property measurements. Work up to now has been on thermophysical property measurements of opaque melts. The lack of experimental techniques for studying internal melt flows in these melts has led to the development of sophisticated numerical models. In what follows, the computational models developed for the investigation of steady-state and transient convection and transport phenomena in both electromagnetically and electrostatically positioned droplets with and without the influence of the external fields are presented. Both 2D and 3D simulations have been performed, and model predictions are compared with measured data whenever available. The modeling results have provided insightful information on the fundamentals governing the convective transport processes of different origins in these droplets. These models and the fundamental understanding gained from the modeling studies have been instrumental in assessing the effect of convection on experimental measurements and its interpretation of space-based experimental data. The future direction with the use of the electromagnetic and electrostatic devices for microgravity applications and the use of the computational modeling to assist in microgravity experimental designs is also discussed.

ELECTROMAGNETIC LEVITATION

Problem Statement

FIGURE 1 shows the TEMPUS device for electromagnetically positioning a free droplet in microgravity.[11] The system consists of two types of coils: (1) the inner four current loops (or heating coils) for sample heating and melting and (2) the outer eight loops (or positioning coils) for sample positioning in space. During the operation, AC currents are impressed through these coils to generate an appropriate magnetic field. Positioning coils use smaller, antiphase currents with a lower frequency to confine the sample. Larger, in-phase