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STUDY OF MAGNETIC DAMPING EFFECT ON CONVECTION AND SOLIDIFICATION UNDER G-JITTER CONDITIONS

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ABSTRACT

As shown in space flight experiments, g-jitter is a critical issue affecting solidification processing of materials in microgravity. This study aims to provide, through extensive numerical simulations and ground based experiments, an assessment of the use of magnetic fields in combination with microgravity to reduce the g-jitter induced convective flows in space processing systems. Analytical solutions and 2-D and 3-D numerical models for g-jitter driven flows in simple solidification systems with and without the presence of an applied magnetic field have been developed and extensive analyses were carried out. A physical model was also constructed and PIV measurements compared reasonably well with predictions from numerical models. Some key points may be summarized as follows: (1) the amplitude of the oscillating velocity decreases at a rate inversely proportional to the g-jitter frequency and with an increase in the applied magnetic field; (2) the induced flow oscillates at approximately the same frequency as the affecting g-jitter, but out of a phase angle; (3) the phase angle is a complicated function of geometry, applied magnetic field, temperature gradient and frequency; (4) g-jitter driven flows exhibit a complex fluid flow pattern evolving in time; (5) the damping effect is more effective for low frequency flows; and (6) the applied magnetic field helps to reduce the variation of solutal distribution along the solid-liquid interface. Work in progress includes developing numerical models for solidification phenomena with the presence of both g-jitter and magnetic fields and developing a ground-based physical model to verify numerical predictions.

I. Introduction

Microgravity and magnetic damping are two mechanisms applied during the melt growth of semiconductor or metal crystals to suppress buoyancy driven flow so as to improve macro and micro homogeneity of the crystals. As natural convection arises from gravity effects, microgravity offers a plausible solution to reduce the convective flow. However, recent flight experiments indicate that residual accelerations during space processing, or g-jitter, can cause considerable convection in the liquid pool, making it difficult to realize a diffusion controlled growth, as originally intended, when experiments were conducted in microgravity [1]. Further studies showed that g-jitter is a random phenomenon associated with microgravity environment and has both steady state and transient effects on convective flow. Since molten metals and semiconductor melts are electrically conducting, magnetic damping may be explored to suppress the unwanted g-jitter induced convection during solidification [2].

The objectives of this project are to: (1) determine the behavior of g-jitter induced convection in a magnetic field, (2) assess the abilities of magnetic fields to suppress the detrimental effects of g-jitter during solidification and (3) develop an experimentally verified numerical model capable of simulating transport processes and solidification phenomena under g-jitter conditions with and without a magnetic field. These goals are to be achieved through both theoretical analyses and ground based laboratory experiments. We have carried out asymptotic analyses and developed 2-D and 3-D numerical models for g-jitter driven flows in simple solidification systems with and without the presence of an applied magnetic field. Research findings obtained from analyses and numerical simulations are reported in refs. [2-7]. A physical model for ground-based measurements has been completed and some measurements of the oscillating convection are currently being taken on the physical model. Comparison of the measurements with numerical simulations is in progress. Numerical and physical models are now being modified to study the solidification phenomena with the presence of both g-jitter and magnetic fields.

II. Analytical Solution for A One-D Simple System

This simple one dimensional analysis is intended to provide some perspective on the asymptotic behavior of magnetic damping effects on g-jitter induced flow in a parallel plate configuration, in which a temperature gradient exists across the channel. A g-jitter field, assumed to follow time harmonic oscillation but spatially independent, acts in the direction parallel to the plates. A DC magnetic field is applied perpendicularly to the plates. Analyses show that the applied field is more effective in suppressing the flows associated with g-jitter with lower frequencies but only has a moderate effect on the high frequency g-jitter flows [3].

III. Development of 2-D and 3-D Finite Element Models

We have developed both 2-D and 3-D numerical models for the transient fluid flow, heat transfer and solutal transport under the influence of g-jitter with and without the presence of an external magnetic field. The model development was based on the finite element solution of the transport equations with the Lorentz forces as a momentum source and entails the modification of our in-house finite element fluid flow and heat transfer code. The numerical models were further tested against the analytical solution for the application of magnetic damping to suppress the g-jitter induced convective flows, and excellent agreement exists between the two approaches [4,5].

The 2-D model was applied to study a simplified Bridgman-Stockbarger system for the melt growth of Ga-doped germanium single crystals. The simplification, among others, treats the solidification front being flat. Numerical simulations illustrate that the application of an external magnetic field reduces the convective velocities in the system studied. Some of the results obtained from 2-D numerical model are given in Figure 1. It is apparent from these figures that the application of the magnetic field reduces the g-jitter induced convective flow effect and thus decreases the solutal striation.

As g-jitter in microgravity is time dependent and changes its direction because of the maneuver of space vehicles, a fully 3-D model is more appropriate. Simulations from 3-D numerical models developed in our group show that the fluid flow driven by g-jitter is very complex and also evolves in time. This can be especially true when all three g-jitter components with composite frequencies and amplitudes are considered. Results illustrate that with the absence of the magnetic field, g-jitter induces strong recirculation in the vertical plane within which it is acting. With a magnetic field applied in the vertical direction, the convective flows and the recirculation loops are suppressed by the opposing Lorentz forces. Fluid flow results in other planes further indicate that with an applied magnetic field, the perturbance from g-jitter may be reduced to a level far smaller than the plug flow resulting from the inlet inertia of the fluid [6]. Table 1 and Figure 2 summarize the results obtained from the 3-D numerical simulations of the magnetic damping effects on the g-jitter induced flows.

IV. Physical Model

A physical model has been developed to partially simulate oscillating behavior of g-jitter force and its effects on natural convection. The detailed physical model construction and entire experimental setup are detailed in a recent thesis [7]. The flow is induced in the system by an oscillating wall temperature gradient combined with the gravitational force. At the present, water is used as a working fluid and a laser-based PIV is used to visualize the thermally induced fluid flow. The measured velocity field was then compared with the finite element computations. Figure 3 compares the calculated and measured oscillating velocity fields. Apparently, the computations agree reasonably well with the measurements and in particular the oscillating flow behavior is revealed in both numerically computed and experimentally measured results.

V. Work in Progress

The work in progress involves extensive experimental measurements and numerical simulations to obtain more information that will help to enhance our fundamental understanding of magnetic damping effects on g-jitter induced flow and solidification phenomena in space processing systems and to help design damping facilities for microgravity applications. Numerical simulations will be continued to study magnetic damping of g-jitter flows and solutal striation and to quantify the effects of the field strength and direction, and the g-jitter frequency, orientation and amplitude, on the convective flows and solutal distribution and evolution in solidification systems. Solidification phenomena will be included in the 2-D model so as to better understand the effects of g-jitter and magnetic fields. Ground-based measurements of oscillating flows and their effects on solidification will be conducted in the physical. The physical measurements will be compared with the numerical model predictions.

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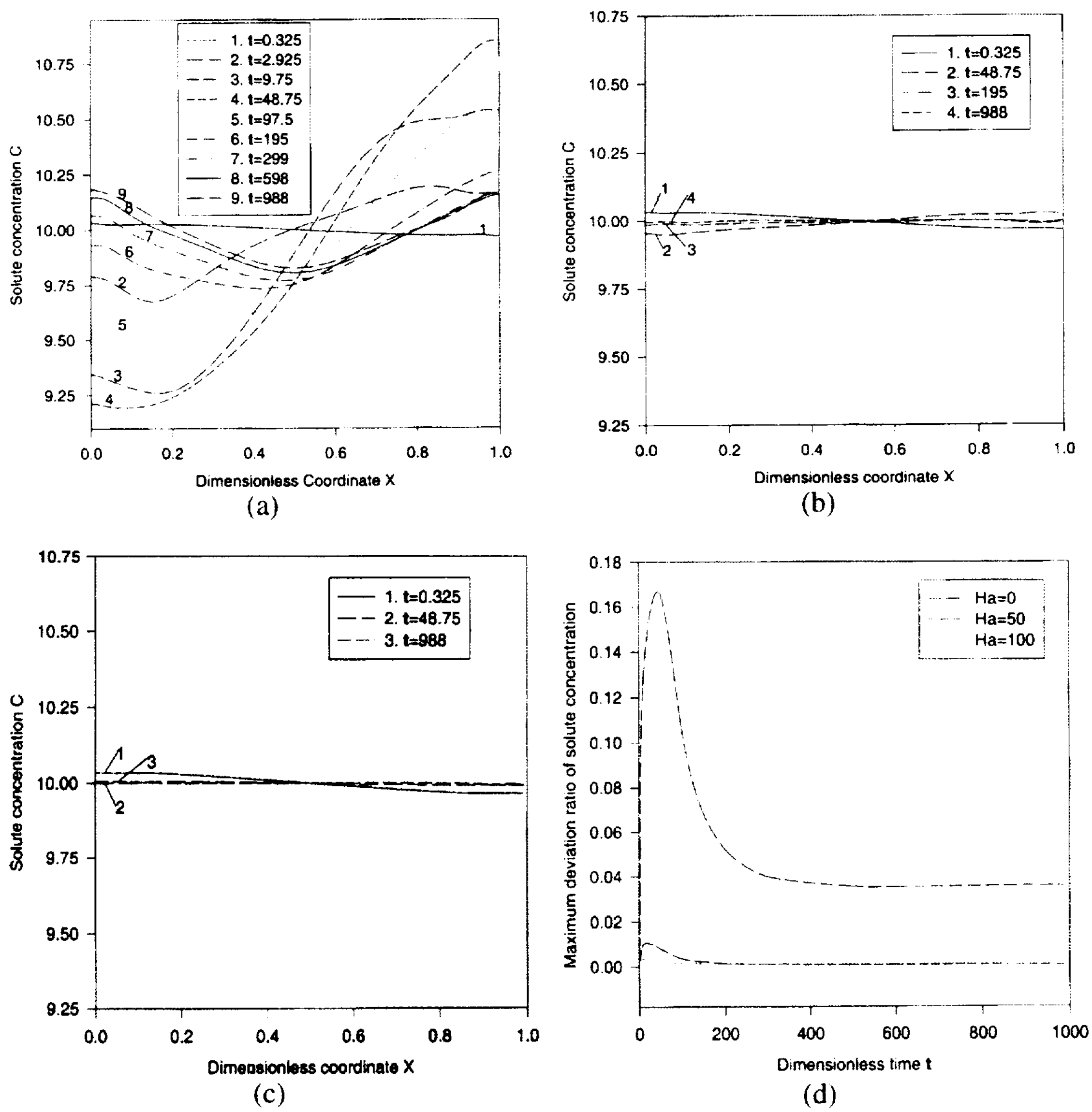


Figure 1. The effect of magnetic fields on the time variation of solutal distribution along the solid-liquid interface (y=0) with a starting steady state in microgravity: (a) Ha=0, (b) Ha=50, (c) Ha=100 and (d) maximum deviation of concentration [5]. The applied magnetic field reduces the convective flow induced by g-jitter and thus the concentration striation. Futhermore, a higher magnetic field results in a more effective damping effect.

Table 1. Summary of the computed results from 3-D numerical model.

g-jitter	U_{max}
$g=g_0 10^{-3}$	0.463
$g=g_0 10^{-4}$	5.56E-02
$g=g_0 10^{-5}$	9.83E-03
$g=g_0 10^{-6}$	5.48E-03
$g=g_0 10^{-3}$ with Ha=100	2.06E-02
$g=g_0 10^{-4}$ with Ha=100	6.56E-03
$g=g_0 10^{-5}$ with Ha=100	5.16E-03
$g=g_0 10^{-6}$ with Ha=100	5.02E-03

* U_{growth} = 0.005 (normalized)

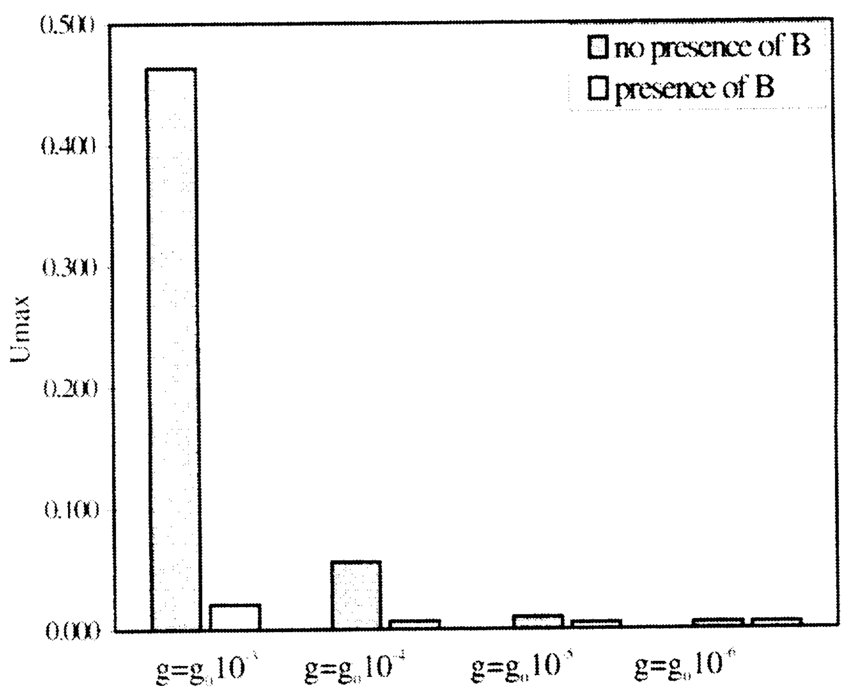
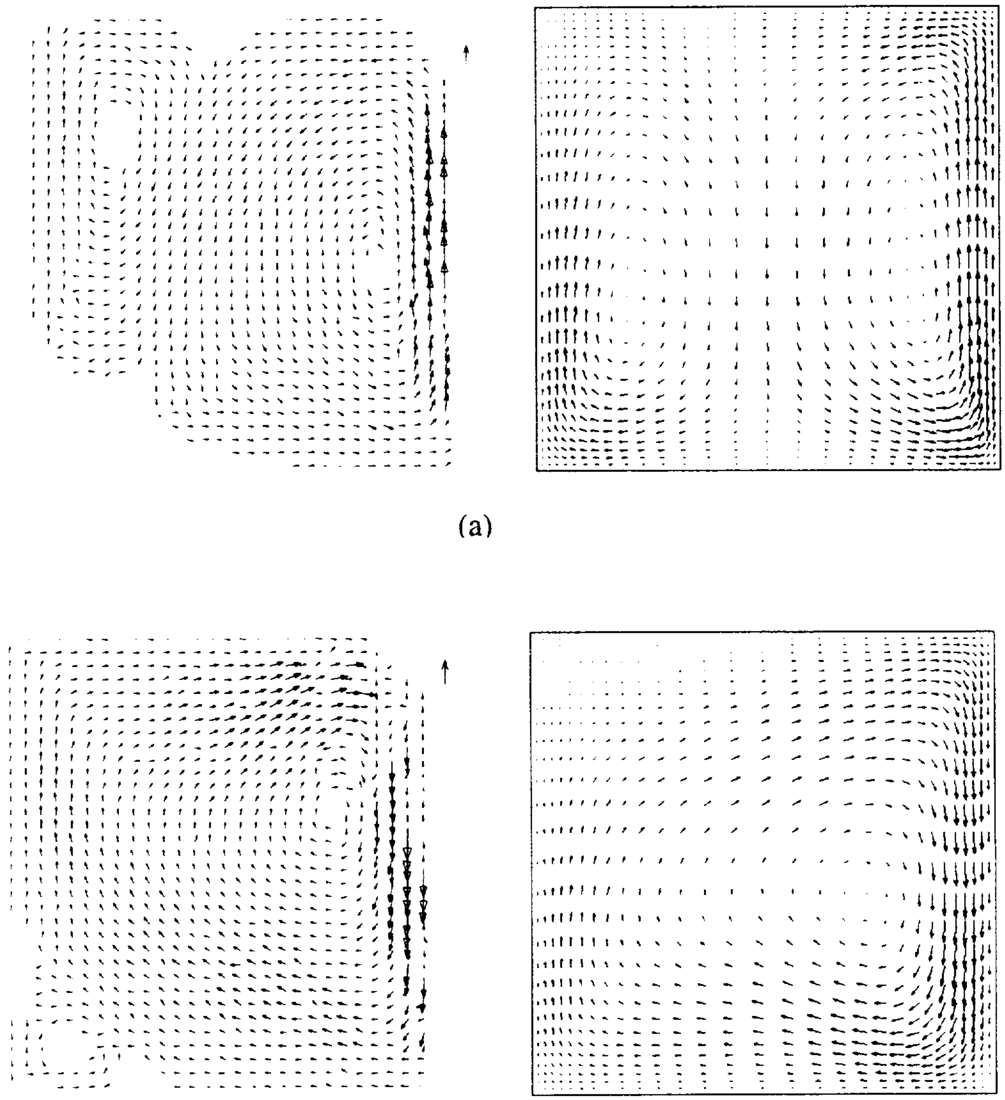


Figure 2. Maximum velocity (in logarithmic scale) calculated using the 3-D numerical model in the presence and absence of an applied magnetic field (Ha=100).



(a)

(b)

Figure 3. Comparison of measured (left) and computed (right) velocity field at diferent times. The flow field is induced by an oscillating wall temperature gradient. (a) maximum velocity: 0.62 mm/s measured vs. 0.57 mm/s computed att=8 sec from the start of an oscillating cycle, (b) maximum velocity: 0.88 mm/s measured vs. 0.93 mm/s computed at t=46 sec from the start of an oscillating cycle. Temperature gradient oscillates at 0.02 Hz [7].