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

S74-29

027151

Ben Q. Li
Department of Mechanical Engineering
Louisiana State University
Baton Rouge, LA 70803
Phone: 504-388-6488
Fax: 504-388-5924
Email: meli@me.lsu.edu

and

H. C. de Groh III
NASA Lewis Research Center
Cleveland, OH 44135
Phone: (216)433-5025
Fax: (216)433-5033
Email: henry@sarah.lerc.nasa.gov

ABSTRACT

As shown by NASA resources dedicated to measuring residual gravity (SAMS and OARE systems), g-jitter is a critical issue affecting space experiments on solidification processing of materials. 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. We have so far completed asymptotic analyses based on the analytical solutions for g-jitter driven flow and magnetic field damping effects for a simple one-dimensional parallel plate configuration, and developed both 2-D and 3-D numerical models for g-jitter driven flows in simple solidification systems with and without presence of an applied magnetic field. Numerical models have been checked with the analytical solutions and have been applied to simulate the convective flows and mass transfer using both synthetic g-jitter functions and the g-jitter data taken from space flight. Some useful findings have been obtained from the analyses and the modeling results. 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 approximately oscillates at 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 numerical simulations and ground-based measurements. Both 2-D and 3-D numerical simulations are being continued to obtain further information on g-jitter driven flows and magnetic field effects. A physical model for ground-based measurements is completed and some measurements of the oscillating convection are being taken on the physical model. The comparison of the measurements with numerical simulations is in progress. Additional work planned in the project will also involve extending the 2-D numerical

model to include the solidification phenomena with the presence of both g-jitter and magnetic fields.

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 indicated 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 [2-7].

The fact that molten metals and semiconductor melts are electrically conducting opens one more avenue to control the convective flow. Less obvious than gravity, this approach is based on the interaction of the liquid motion with an externally applied magnetic field. This interaction gives rise to an opposing Lorentz force that results in a reduction (or damping) of melt flow velocities and may be explored to suppress the unwanted g-jitter induced convection during solidification.

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 so far completed asymptotic analyses based on the analytical solutions for g-jitter driven flow and magnetic field damping effects for a simple one-dimensional parallel plate configuration, and developed both 2-D and 3-D numerical models for g-jitter driven flows in simple solidification systems with and without presence of an applied magnetic field [9-13]. Numerical models have been checked with the analytical solutions and have been applied to simulate the convective flows and mass transfer using both synthetic g-jitter functions and the g-jitter data taken from space flight. Some useful findings obtained from the analyses and the modeling results are reported in ref. [9-13]. Both 2-D and 3-D numerical simulations are being continued to obtain further information on g-jitter driven flows and magnetic damping effects. A physical model for ground-based measurements is completed and some measurements of the oscillating convection are being taken on the physical model. The comparison of the measurements with numerical simulations is in progress. Also, the 2-D numerical model is being modified to allow for 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 asymptotic behavior of the magnetic damping effects on g-jitter induced flow in a parallel plate configuration. A temperature gradient is established between two infinitely large parallel plates. A g-jitter field, which is 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.

Some results are selectively presented in Figures 1 to 2. Figure 1 shows the 3-D view of the natural convection distribution across the width of the channel induced by g-jitter without an applied magnetic field for different times. The quantity plotted along the vertical axis shows the velocity in the channel driven by synthetic g-jitter functions, which are assumed to follow a Fourier series in time. The fluid flow profile across the channel with applied magnetic fields illustrated in Figure 2. Clearly, as a limit, the flow can be damped entirely if a large enough magnetic field is applied. Also, a magnetic field is effective in damping flows induced by g-jitter with larger component and lower frequency. Further studies also 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.

III. DEVELOPMENT OF 2-D FINITE ELEMENT MODEL

We have developed a numerical model 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 to study the g-jitter induced flow and magnetic damping effects. Our finite element code, during the course of its development, has been extensively compared with various commercial packages including FIDAP, FLOW3D, and FLUENT. The numerical model is further tested against the analytical solution for the application of magnetic damping to suppress the g-jitter induced convective flows. Figure 3 compares the numerical results and analytical solutions for a simplified parallel plate configuration. Clearly excellent agreement exists between two approaches.

The 2-D model was applied to study a simplified Beidgman-Stockbarger system for the melt growth of Ga-doped germanium single crystals. The simplification, among others, treats the solidification front being flat. Some of the results obtained from 2-D numerical model are given in Figures 4 to 6. It is seen from Figure 4 that the application of an external magnetic field reduces the convective velocities in the system studied. Figures 5 and 6 compare the time evolution of the solutal distribution along the solidification front with and with an applied magnetic field. With the magnetic field, solutal variation along the interface is much reduced. It is noteworthy that the solutal element still varies with time at a location on the interface but the amplitude of the variation is also much reduced with the applied magnetic field.

IV. DEVELOPMENT OF 3-D FINITE ELEMENT MODEL

We also have developed a 3-D numerical model for the study of transient fluid flow, heat transfer and mass transport as well as magnetic damping phenomena induced by g-jitter in microgravity with and without presence of an applied magnetic field. The model development is based on the finite element solution of the transient 3-D Navier-Stokes equations and heat/mass balance equation along with the Maxwell equations. 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.

The 3-D model described above has been applied to study the g-jitter driven flows, heat/mass transfer and magnetic damping phenomena associated with a simplified Beidgman-Stockbarger system for the melt growth of Ga-doped germanium single crystals. Again to simplify the calculations, the liquid-solid interface is assumed to be flat. Results 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 a composite frequency and amplitudes are considered. The temperature distribution, however, remains the same, suggesting that heat transfer in the system is primarily by conduction because of a small Prandtl number of the melt.

Figures 7 and 8 illustrate the magnetic damping effects on the g-jitter induced flows. Clearly, with the absence of the magnetic field, g-jitter induces strong recirculation in the vertical plane within which it is acting, as appear in Figure 7. With a magnetic field applied in the vertical direction, the convective flows and the recirculation loops are suppressed by the opposing Lorentz forces, as is evident in Figure 8 where the effect of inlet flow from the upper flat surface becomes more visible. Fluid flow results in other planes further indicate that with an applied magnetic field, the perturbance from g-jitter may be reduced to the level far smaller than the plug flow resulting from the inlet inertia of the fluid.

IV. WORK IN PROGRESS

The work in progress involves extensive experimental measurements and additional 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.

Extensive numerical simulations will be continued to study magnetic damping of g-jitter flows. Information will be obtained 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 will be conducted in the physical model that has just been completed and is being fine tuned. The physical measurements will be compared with the numerical model predictions. Additional experiments are also planned at NASA Lewis research center and compared with model predictions. The numerical models will be refined in light of the comparison. The refined models will be applied to carry out further studies of damping effects on velocity distribution, temperature distribution, solid-liquid interface and solute distribution during solidification with both synthetic g-jitter functions and the g-jitter data taken during space flight.

V. REFERENCES

[1] Lehoczky, S., Szofran, F. R. and Gillies, D. C. (1994). Growth of solid solution single crystals. Second United States Microgravity Payload, Six Month Sciences Report, NASA MSC.

[2] Alexander, J. I. D. (1990) *Microgravity Sci Tech.*, vol. 3, P. 52.

[3] Alexander, J. I. D. (1994). *Microgravity Sci. Tech.*, Vol. 2, p.131.

[4] Alexander, J. I. D., Amiroudine, S., Quazzani, J. and Rosenberger, F. (1991) *J. Crystal Growth*, Vol. 113, p.21.

[5] De Groh, H. C. and Nelson, E. S. (1994). On residual acceleration during space experiments. ASME Winter Annual Meeting, Chicago, IL, HTD-Vol. 290, p. 23.

[6] Nelson, E. S., (1991). An examination of anticipated g-jitter on space station and its effects on materials processes. NASA TM 103775.

[7] Sabhapathy, P. and Salcudean, M. E. (1991). *J. Crystal Growth*, Vol. 113, p. 164.

[8] B. Q. Li, "G-jitter induced flows in a transverse magnetic field," *Int. J. Heat & Mass Trans.*, Vol. 39, No. 14, pp. 2853-2860, 1996.

[9] B. Q. Li, "The effect of magnetic fields on low frequency oscillating natural convection," *Int. J. Eng. Sci.*, Vol. 34, No. 12, 1996, pp. 1369-1383.

[10] Pan and B. Q. Li, "Effect of magnetic fields on oscillating mixed convection," *Int. J. Heat & Mass Transfer*, Vol. 41, No. 17, 1998, pp. 2705-2710.

[11] B. Pan, B. Q. Li and H. C. de Groh "Magnetic damping of g-jitter induced flow in microgravity," *Spacebound-97*, Montreal, May, 1997 (published in CD-ROM, ed: R. A. Schiffman), Canadian Space Agency, Canada.

[12] B. Pan, B. Q. Li and H. C. deGroh, "Magnetic damping of g-jitter induced oscillating convection," *Joint Xth European and Vith Russain Symp. on Phys. Sci. In Mcirogravity*, June 1997, pp. 305-308.

[13] D-Y Shang, B. Q. Li and H. C. de Groh, "Magnetic damping of g-jitter driven flows: 3-D calculations," *Pan-Pacific Basin Workshop*, July 1998, accepted.

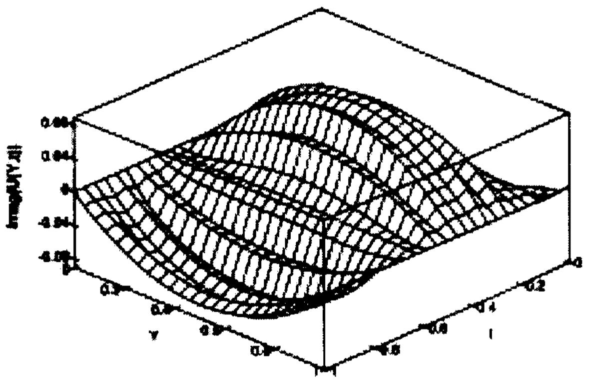

Figure 1. The flow field induced by a combination of two g-jitter components with distinct frequencies ($\Omega_2=10\Omega_1=100$) but the same magnitude ($g_2=g_1=1$, $T_2=T_1$) without a magnetic field. $t=\Omega_1\tau/2\pi$.

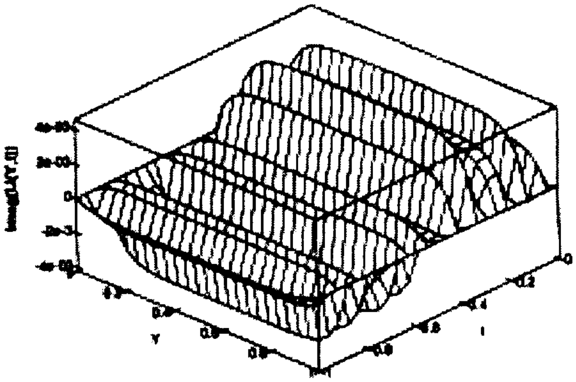

Figure 2. Effect of magnetic field on g-jitter induced flows ($\Omega_2=10\Omega_1=100$, $g_2=g_1=1$, $T_2=T_1$). Ha=20, and $t=\Omega_1\tau/2\pi$. Note that in comparison with Fig. 1, the velocity is reduced by a factor of about 10.

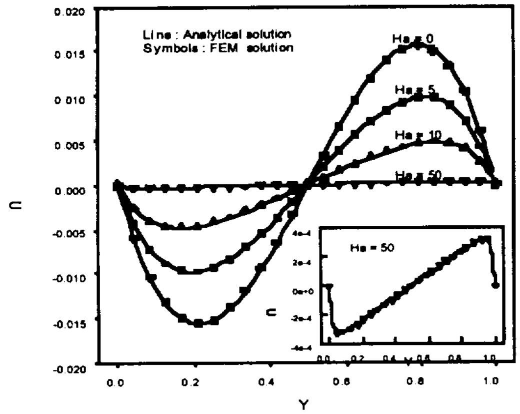

Figure 3 Comparison of the 2-D numerical and the analytical solutions for convective flows in a parallel plate channel: *Y* the location between the plate and *U* the fluid flow velocity, both nondimensionalized.

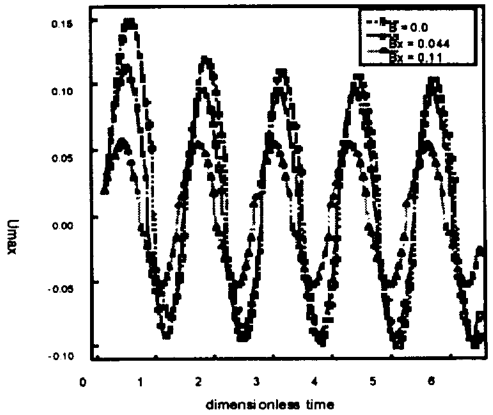

Figure 4 Dependency of maximum flow velocity in the Ga-doped germanium melt on the applied magnetic field (2-D model): single frequency g-jitter, $g=10^{-3}$ and $f_n=0.1$ acting in the x-direction.

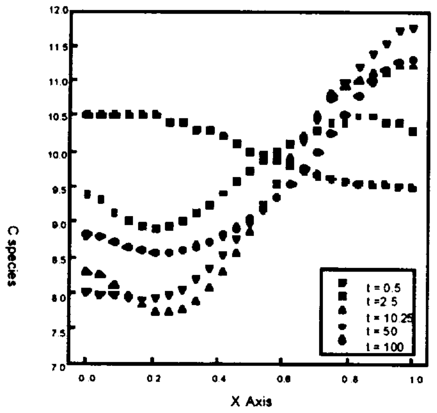

Figure 5 Concentration distribution along the interface at different times without an imposed magnetic field (2-D model): $g/f - 10^{-2},10^{-3},10^{-4}\ g_o/1,0.1,0.01$.

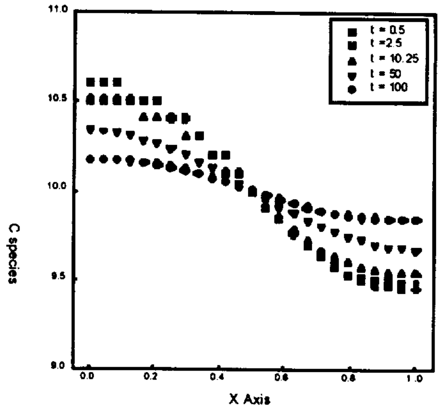

Figure 6Concentration distribution along the interface at different times with a magnetic field B_x=0.22 (2-D model): $g/f - 10^{-2},10^{-3},10^{-4}\ g_o/1,0.1,0.01$.

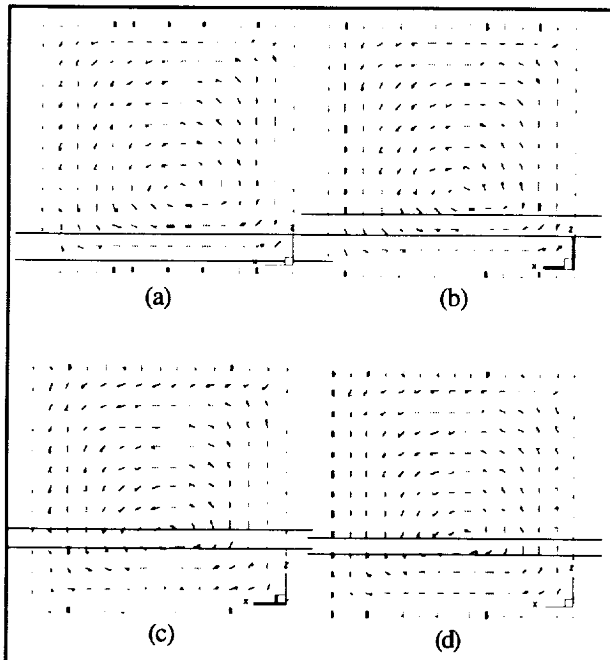

Figure 7 Velocity field in the x-z plane at different time steps (3-D model, viewed from the positive y-axis, g-jitter acting in the x-direction with amplitude=1x10^{-3}g$_0$and freqneucy=0.1 Hz): (a) t=5 sec, (b) t=10 sec, (c) t=35 sec, and (d)=40 sec.

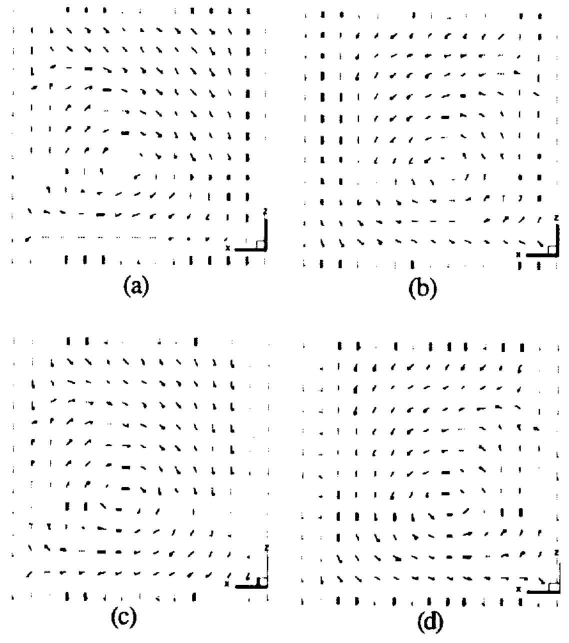

Figure 8 Magnetically damped velocity field in the x-z plane corresponding to Figure 7 but with an applied magnetic field in the y-direction B=0.22 Tesla.