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NON-LINEAR RESONANCE OF FLUIDS IN A CRYSTAL GROWTH CAVITY

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INTRODUCTION

In the microgravity environment, the effect of gravity on fluid motion is much reduced. Hence, secondary effects such as vibrations, jitters, surface tension, capillary effects, and electro-magnetic forces become the dominant mechanism of fluid convection. Numerous studies have been conducted to investigate fluid behavior in microgravity with the ultimate goal of developing processes with minimal influence from convection. Industrial applications such as crystal growth from solidification of melt and protein growth for pharmatheutical application are just a few examples of the vast potential benefit that can be reaped from material processing in space.

However, a space laboratory is not immune from all undesirable disturbances and it is imperative that such disturbances be well understood, quantifiable, and controlled. Non-uniform and transient accelerations such as vibrations, g-jitters, and impulsive accelerations exist as a result of crew activities, space vehicle maneuvering, and the operations of on-board equipment. Measurements conducted on-board a U. S. Spacelab showed the existence of vibrations in the frequency range of 1 to 100 Hz.[1], with a dominant mode of 17 Hz and harmonics of 54 Hz. The observed vibration is not limited to any coordinate plane but exists in all directions. Similar situation exists on-board the Russian MIR space station. Due to the large structure of its design, the future International Space Station will have its own characteristic vibration spectrum.

It is well known that vibration can exert substantial influence on heat and mass transfer processes, thus hindering any attempts to achieve a diffusion-limited process. Experiments on vibration convection for a liquid-filled enclosure under one-g environment [2,3] showed the existence of different flow regimes as vibration frequency and intensity changes. Results showed the existence of a resonant frequency, near which the enhancement is the strongest, and the existence of a high frequency asymptote. Numerical simulations of vibration convection have been conducted by Yurkov[4], Fu and Shieh[5], and by Wang[6]. These analyses considered a two-dimensional air-filled cell under weightlessness condition and showed results similar to those of the experiments.

It is not yet known whether resonance convection can be triggered by g-jitter alone or whether it requires the interaction of g-jitter with other convective forces in low gravity. An order of magnitude analysis, however, can be used to show the dependence of the resonance frequency on the fluid Prandtl number. Even though the onset of resonance convection may depend on other factors, results indicates that fluids with low Prandtl numbers are more susceptible to resonance than those with high Prandtl numbers. The current study is aimed at gaining additional insights to this problem using germanium as working fluid. Germanium was chosen for this analysis because of its common usage in solidification process and its relatively low Prandtl number (Pr = 0.02).

ANALYTICAL MODEL

The Navier-Stokes equations for an incompressible fluid with Boussinesq approximation were used for this analysis. These equations can be non-dimensionalized using a characteristic velocity based on thermal diffusion, α, and the dimension of the cell, L. For a two-dimensional problem in which the sinusoidal vibration is along the same direction as the residual acceleration, the following equations cam be used:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \quad (1)$$

$$\frac{\partial U}{\partial \tau}+U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=-\frac{\partial P}{\partial X}+\Pr\nabla^2 U \quad (2)$$

$$\frac{\partial V}{\partial \tau}+U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}=-\frac{\partial P}{\partial Y}+\Pr\nabla^2 V + \Pr[Ra+G\omega\sin(\tau\omega)]\theta \quad (3)$$

$$\frac{\partial \theta}{\partial \tau}+U\frac{\partial \theta}{\partial X}+V\frac{\partial \theta}{\partial Y}=\frac{\partial^2 \theta}{\partial X^2}+\frac{\partial^2 \theta}{\partial Y^2} \quad (4)$$

Here U and V are the non-dimensional velocity components, Pr the Prandtl Number, Ra the Rayleigh number, G the Grashof Number, and ω the non-dimensional circular frequency. Notice that the forcing term in equation (3) is proportional to the product of Prandtl number, the temperature differential, and the buoyancy effect of acceleration. The buoyancy term consists, in general, of two components, one due to the residual acceleration and one due to the oscillation force. The constant acceleration is expressed in terms of the Rayleigh number, and the applied oscillation is expressed in terms of the product of the Grashof number, the circular frequency and a time varying sine function.

NUMERICAL INVESTIGATION

Equations (1-4) were solved numerically using the NASA developed two-dimensional Finite Difference Navier-Stokes solver (FDNS2D) [Ref. 7]. The working fluid is germanium which is a representative fluid used in solidification from melts. The properties of germanium along with that of water and air are given in Table 1.

Property	Water	Air	Germanium
Kinematic Viscosity (m2/s)	9.8260E-07	1.6000E-05	3.3160E-07
Density (kg/m2)	9.9740E+02	1.1650E+00	6.1000E+03
Thermal Diffusivity (m2/s)	1.4490E-07	2.2860E-05	1.5120E-05
Expansion Coefficient (1/K)	2.7720E-04	3.3000E-03	1.2600E-04
Prandtl number	7.00	0.70	0.02

Table 1. Summary of Fluid Properties

The calculation domain of the cavity is divided into a finite difference mesh of 31 by 31. The fluid was initially assumed in a quasi-static condition with a constant temperature difference of 100k maintained across two opposing surfaces. At time zero, a continuous vibration acceleration of constant amplitude is applied in the direction normal to the temperature gradient. Transient solutions were obtained for different vibration frequencies using a time marching technique. Iterations at each time step were used to ensure convergence. Figure 1 depicts the

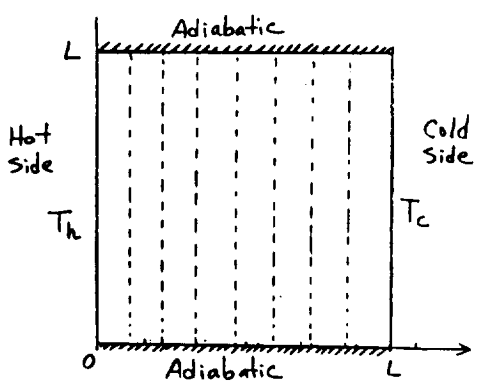

Figure 1. Geometry of Cavity

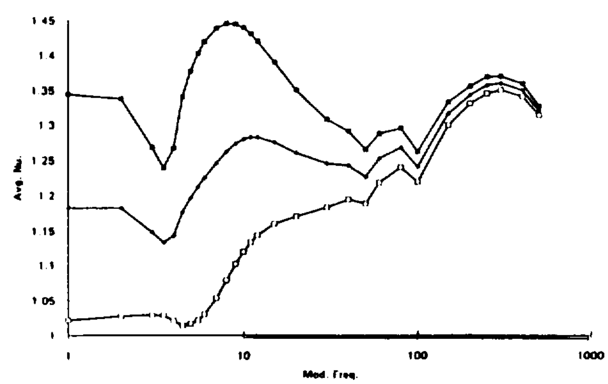

Figure 2. Average Nu Plot for Germanium

RESULTS & DISCUSSIONS

Numerical results for germanium (Pr = 0.02) in a cavity of 1 cm squared in a zero gravity environment will be reported. A Grashof number of 10^{+4} was used in the analysis. Figure 2 shows the existence of several different flow regimes as the vibration frequency increases. Expressed in terms of the averaged Nusselt number, the result indicated an increase of heat transfer from the hot wall to the cold wall at low vibration frequencies. This heat transfer rate peaks out near a resonance frequency, then went through a transition regime of instability. Finally it settles to an asymptote at very high frequencies. This trend is very similar to that of air, shown in Figure 3 from a previous study [Ref. 6]. However, the transition between the flow regimes occurs at much lower frequencies, and the enhancement of heat transfer rate is less prominent for germanium.

The resonance regime for germanium is found between the non-dimensional frequencies of 3 and 10, which translates to a frequency of 0.247 Hz for a cell of 1 cm. This frequency is much smaller than that of air which exists in the range of 10 to 30 Hz. This difference is due to the difference in fluid properties, especially due to the fluid viscosity and fluid Prandtl number. A plot of the steady state temperature at a point near the top of the mid-plane is shown in Figure 4. It shows that at lower vibration frequencies the temperature variation is high, and its mean value is close to the medium value between the two side walls. As the frequency increases, the temperature variation becomes smaller, and the mean value moves toward a lower value. A review of temperature data at several to the direction of vibration, with the top boundary always at higher temperature than the lower boundary. This has been attributed to the persistence of flow as a result of the initial impulse.

Time variation of the averaged Nusselt number and temperature at three points along the mid-plane for a few selected frequencies are given in Figures 5 and 6, respectively. The three frequencies selected ω = 3, 10, and 100 represent regimes of transition, resonance, and high frequency vibration convection. Notice the existence of the double peaks in Nusselt number during each cycle of vibration for ω = 3 in Figure 5. This is due to the complete reversal of the temperature about the mid-plane of the cavity during an oscillating cycle of vibration, as shown clearly in the top portion of Figure 6.

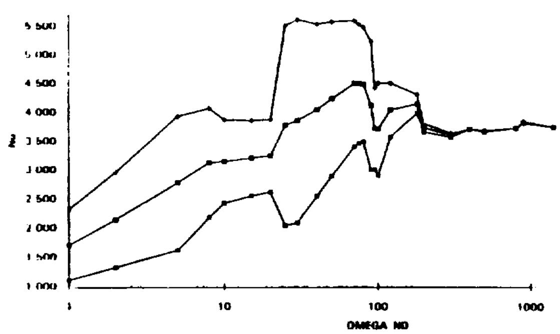

Figure 3. Average Nu Plot for Air

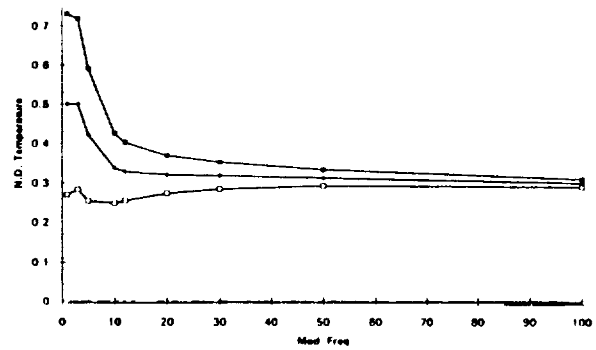

Figure 4. Temperature Plot for Mid-Plane

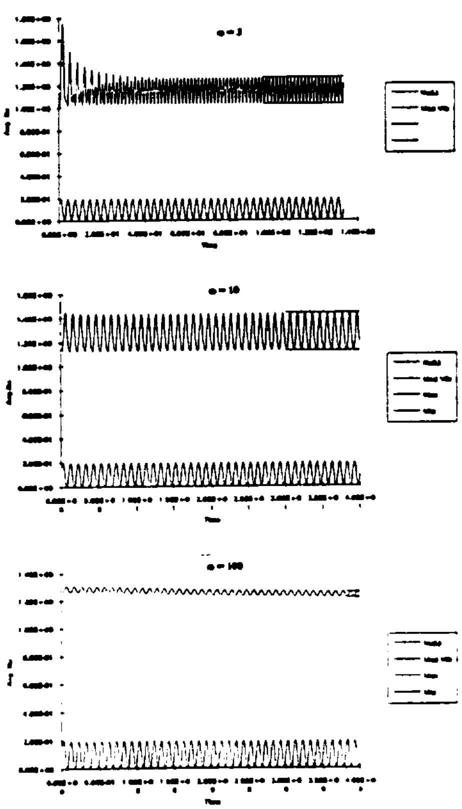

Figure 5. Variation of Nusselt Numbers for ω = 3 (top), 10 (middle), and 100 (bottom)

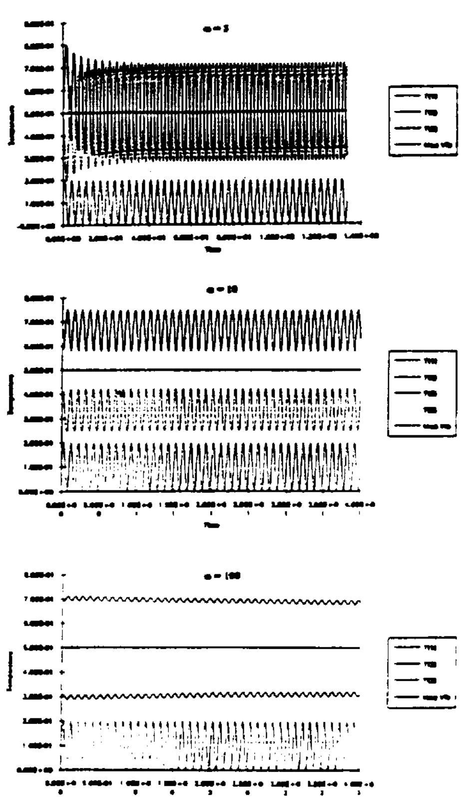

Figure 6. Variation of Temperature for ω = 3 (top), 10 (middle), and 100 (bottom)

CONCLUSIONS & RECOMMENDATIONS

Results of a numerical simulation of vibration convection of a crystal growth cavity in zero gravity showed the existence of different flow regimes at different vibration frequencies. Results showed that the division of the flow regimes and the peak heat transfer rate dependent on the Prandtl number of the working fluid. A complete reversal of temperature profiles about the cavity mid-plane at low vibration frequencies leads to heat transfer rate which oscillates at twice the vibration frequency. At higher vibration frequencies, the fluid near the top portion of the cavity is consistently hotter than the fluid near the bottom, resulting in an internal heat flow in the direction normal to the applied temperature gradient. At very high frequencies, the flow reaches an asymptote, and the heat transfer rate becomes independent of the vibration frequency.

Additional analyses are needed to investigate the effects of cavity geometry, e.g. cylindrical shape, or one with different length to height ratios. Effects due to non-zero gravity also need to be considered. Experimental programs aimed at verifying the numerical results are under consideration. A flight experiment will eventually be needed to verify the results of vibration effects on fluid convection in micro-gravity conditions.

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