N95- 19013

30936
P_9

1994

NASA/ASEE SUMMER FACULTY FELLOWSHIP PROGRAM

MARSHALL SPACE FLIGHT CENTER
THE UNIVERSITY OF ALABAMA

EFFECTS OF VIBRATION (G-JITTERS) ON CONVECTION IN MICRO-GRAVITY

Prepared By:	Francis C. Wang, Ph.D.
Academic Rank:	Senior Research Engineer
Institution:	University of Alabama in Huntsville Research Institute
NASA/MSFC:	
Laboratory:	Space Sciences Laboratory
Division:	Microgravity Science & Applications Division
Branch:	Crystal Growth & Solidification
MSFC Colleagues:	Charles R. Baugher, MSFC Colleague N. Ramachandran, Ph.D., USRA Colleague

INTRODUCTION

To obtain high quality crystals, it is desirable to maintain a diffusion-limited transport process and a planar solidification surface between the solid and the melt during the crystal growth process. Due to the presence of buoyancy-driven convection, however, this situation is difficult to maintain on Earth. The microgravity environment of an orbiting space laboratory presents an alternative worth pursuing. With reduced gravity, convection is very much suppressed in a space laboratory, making the environment more conducive for growing crystals with better quality.

However, a space laboratory is not immune from any undesirable disturbances. 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 mission showed the existence of vibrations in the frequency range of 1 to 100 Hz. (See Ramachandran, Baugher, and Rogers, "Acceleration Environment on the Space Shuttle and Its Impact On Thermo-Solutal Fluid Mechanics," ASME Winter Annual Meeting, 1993). It was reported that a dominant mode of 17 Hz and harmonics of 54 Hz were observed and these were attributed to antenna operations. The vibration is not limited to any single plane but exists in all directions. Some data from the Russian MIR space station indicates the existence of vibration also at this frequency range.

It is known [Refs. 1-10] that vibration can exert substantial influence on the fluid flow and heat transfer characteristics, such as changing the local or total heat transfer rate, affecting the transition from conduction heat transfer to convection, and from laminar flow to turbulent flow. It can also change the boundary layer thickness thus affecting mass transfer. Hence the presence of vibration will have negative impact on achieving the diffusion-limited process in a space laboratory.

This report summarizes the work conducted at NASA MSFC during the tenure of the 1994 Summer Faculty Fellowship Program. It consists of two parts: a brief summary of an extensive literature search and review on vibration convection; and the results of a numerical study of vibration convection in an enclosure under zero gravity.

REVIEW OF LITERATURE ON VIBRATION CONVECTION

An extensive literature search has been conducted on vibration convection studies conducted for the past three decades. Although most works reported in the open literature are included, the emphasis has been on works conducted in the former Soviet Union. It was found that the Russians have conducted quite extensive studies, and an analytical method has been developed for studying high frequency vibration convection. A brief summary of the review is given below. Two areas covered in this summary are the effects of vibration on fluid stability, and vibration effects on convection in fluid-filled enclosures.

Stability of Fluid Layer

Stability of fluid layers subject to vibration modulation has been the subject of analytical and experimental studies for many years. Most analyses were conducted using the linear perturbation method. In the Russian studies, a time-averaged method has been used for flows with high frequency vibrations. This method, first proposed by Zenkovskaya and Simonenko [Ref. 11], utilizes a time-averaged quantity to represent the effects of vibration acceleration. Closed form solutions were obtained under certain conditions. Problems studied include vibration convection in a rectangular cavity [Ref. 12], vibration convection in a cylindrical cavity [13], flow about a uniformly heated cylinder [14] and others. It was found that vibration modulation can alter the stability criteria. Implications to fluid behaviors under zero gravity were also made. Detailed description of this method, its development and application can be found in the treatises of Refs. 15 & 16.

Experimental studies of stability were conducted by Zavarykin et al. [Refs. 17, 18] for fluid layers subject to heating and vibration. In their experiments, the stability of a vertical and a horizontal fluid layer were studied when subject to vibrations. Results indicate that vertical vibration can suppress convection instabilities in fluid layers that are vertically stratified in temperature. The results also indicate that vibration excitations in the horizontal direction can destablize the fluid. These results support the predictions obtained from analyses.

Vibration Convection In An Enclosure

Early experiments conducted by Forbes, Carley and Bell [Ref. 4] showed that heat transfer rate for a liquid-filled vertical rectangular enclosure is enhanced when sinusoidal vibration is applied. Their experiments indicated the existence of a resonant frequency, near which the enhancement is the strongest. Similarly, Ivanova and Kozlov [19] applied vibrations to a horizontal cylindrical layer under convection and reported the existence of three flow regimes based on vibration intensity. Effects of transient vibrations were studied by Ivanova who conducted an experiment to study cooling of fluids between two concentric cylinders [Ref. 20].

As the frequency of vibration reaches a certain range, phenomena such as resonance and the change of heat transfer modes may occur. These phenomena, usually transient and highly non-linear, cannot be analyzed using the linearized methods. Full equations must be used and numerical solutions are usually required. Studies of vibration convection in an enclosure have provided significant insight into these complex phenomena. Heat transfer rate across the enclosure walls, given in terms of the average Nusselt number, has been used as a direct measure of the intensity of interactions between vibration and convection.

The existence of synchronous, sub-harmonic and relaxation oscillations which resulted from the non-linear interaction of vibration and convection has been studied by Gresho and Sani [6]. Numerical studies of this phenomenon were conducted by Yurkov [Refs. 21, 22], by Biringen & Danabasoglu [23] and others. Most recently, a numerical simulation of vibration convection in a two-dimensional cavity was conducted by Fu and Shieh [24] which covered a wide range of vibration frequencies. Their study also covered several different values of residual gravity including zero gravity. Their results showed the existence of different flow regimes confirming the findings of the Russians [Ref. 25]. A summary of these results are given below:

- The key parameters of vibration convection are the Prandtl number, the vibration frequency, and the Grashof number (G).

- The effect of vibration is more prominent in frequency variations than in amplitude variations.

- The effect of vibration reaches an asymptote at high frequencies.

- There exists a resonance regime for which heat and mass transfer are greatly enhanced.

Figure 1. shows the variation of the average Nusselt number vs. vibration frequency for a fluid-filled cavity subject to sinusoidal vibrations in the direction normal to the temperature gradient. Figure 1(a) is from [Ref. 25], while figure 1(b) is from [Ref. 24]. A quick analysis of the data from Ref. 24, indicates that the resonance frequency could be in the range of 1 to 100 Hz.

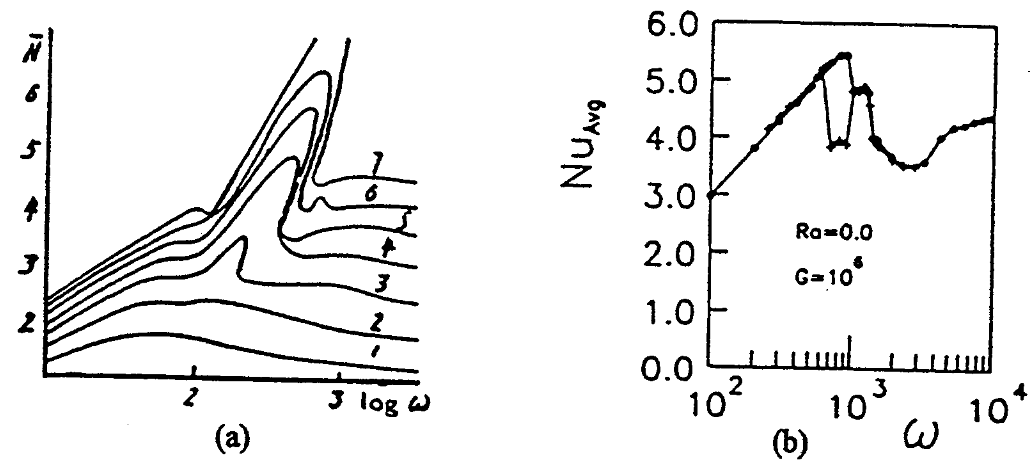


Figure 1. Results of Past Studies

A NUMERICAL STUDY OF VIBRATION CONVECTION

To demonstrate the effects of vibration on convection in a weightlessness environment, a numerical simulation of a crystal growth cell was conducted using a two-dimensional fluid-filled cell. This cell is subjected to a lateral temperature gradient and a vertical sinusoidal vibration. Fluid flow and heat transfer rates were obtained for a wide range of vibration frequencies. Results of the numerical simulation demonstrate the complex processes occurring inside the cell, and supports the existence of resonance regime and the high frequency asymptotes as were reported in Refs. 24 and 25.

Non-Dimensional Equations

The basic equations for analysis are the equations for an incompressible fluid with Boussinesq approximation. Casting in non-dimensional form using a characteristic velocity based on thermal diffusion, α, and the length of the cell, L, we obtain the following equations

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

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

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

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

Here θ, P, U, V, and τ are non-dimensional variables. Other parameters are Pr the Prandtl Number, Ra the Rayleigh number, G the Grashof Number, and ω the non-dimensional circular frequency. Here we have assumed that the sinusoidal vibration is imposed in the vertical (Y) direction, same as the residual acceleration. Figure 2 depicts the domain of calculations.

Solution Method

Equations (1-4) are solved numerically using the NASA developed two-dimensional Finite Difference Navier-Stokes solver (FDNS2D). A finite difference mesh of 31 by 31 are used to calculate flow properties in the interior of the cavity. The quasi-static condition was used as the initial condition and transient solutions were obtained for different vibration frequencies using a time marching technique. Iterations at each time step is used to ensure convergence.

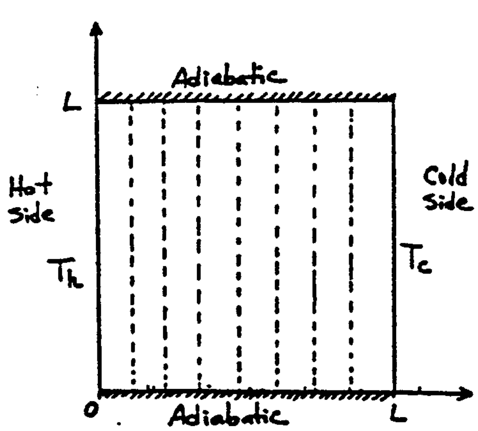


Figure 2. Rectangular Cavity

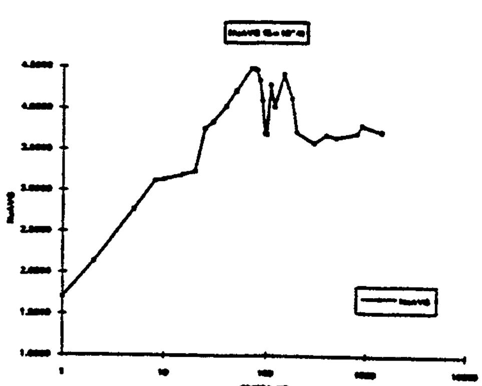


Figure 3. Results of Current Study

RESULTS & DISCUSSIONS

Numerical calculations were conducted for air (Pr = 0.7) in a cavity of 1 cm squared in a zero gravity environment (Ra = 0). The vibration acceleration is applied in the Y-direction while a temperature difference of 100 k is maintained between the walls at X=0, and X=1 as shown in Figure 2. Results of numerical calculations are shown in Figures 3 through 5 for the case of $G = 10^{+4}$. From the variation of Nusselt number as shown in Figure 3, it is evident that several different flow regimes exist as vibration frequency changes. This variation follows the same trend as shown in Figure 1, supporting the findings of previous studies. The resonance frequency obtained here is within the range as predicted in Ref. 24.

Figure 4 shows the variation of the average Nusselt number as a function of time for six different vibration frequencies. These curves showed the strong interactions between convection and vibration at different frequencies. At low vibration frequencies, as shown in Fig. 4 (a), the flow is oscillatory at twice the vibration frequency. At intermediate vibration frequencies, shown in Fig. 4 (b), instability has set in and multiple frequencies showed up. As the frequency increases further resonance is reached. As shown in Fig. 4 (c), the flow showed large variations in Nusselt number. At even higher frequencies, as shown in Figs. 4(d) and (e), a transition period occured with oscillations of multiple frequencies. At extremely high frequencies, as shown in Fig. 4(f), high frequency vibration convection is established. The flow settles rapidly after an initial response to the vibration. The Nusselt number peaked first then levels off to its asymptote.

Details of the flow field can be shown by plotting the stream functions, the isotherms, and the velocity vectors at different stages of its development. Shown in Figure 5 are the plots for a high frequency vibration convection ($\omega = 1400$). Figure 5(a) shows the stream functions (left row), the isotherms (middle row), and the velocity vectors (right row) of the first two cycles. Figure 5(b) shows the same after 10 cycles of vibrations. Notice the thin thermal boundary layers near the isothermal walls which cause the Nusselt number to peak. Figure 5(c) shows the fully developed flow which has reached the asymptote.

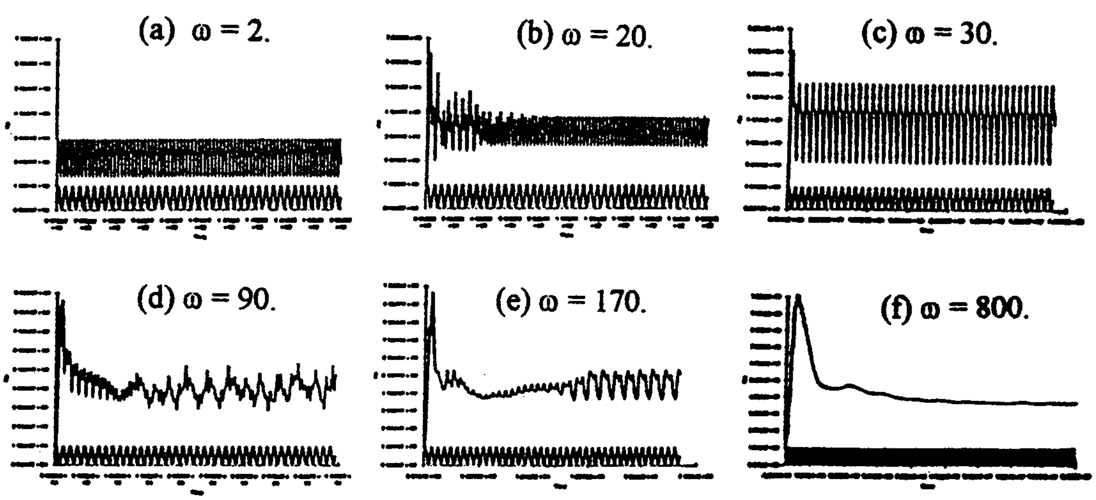
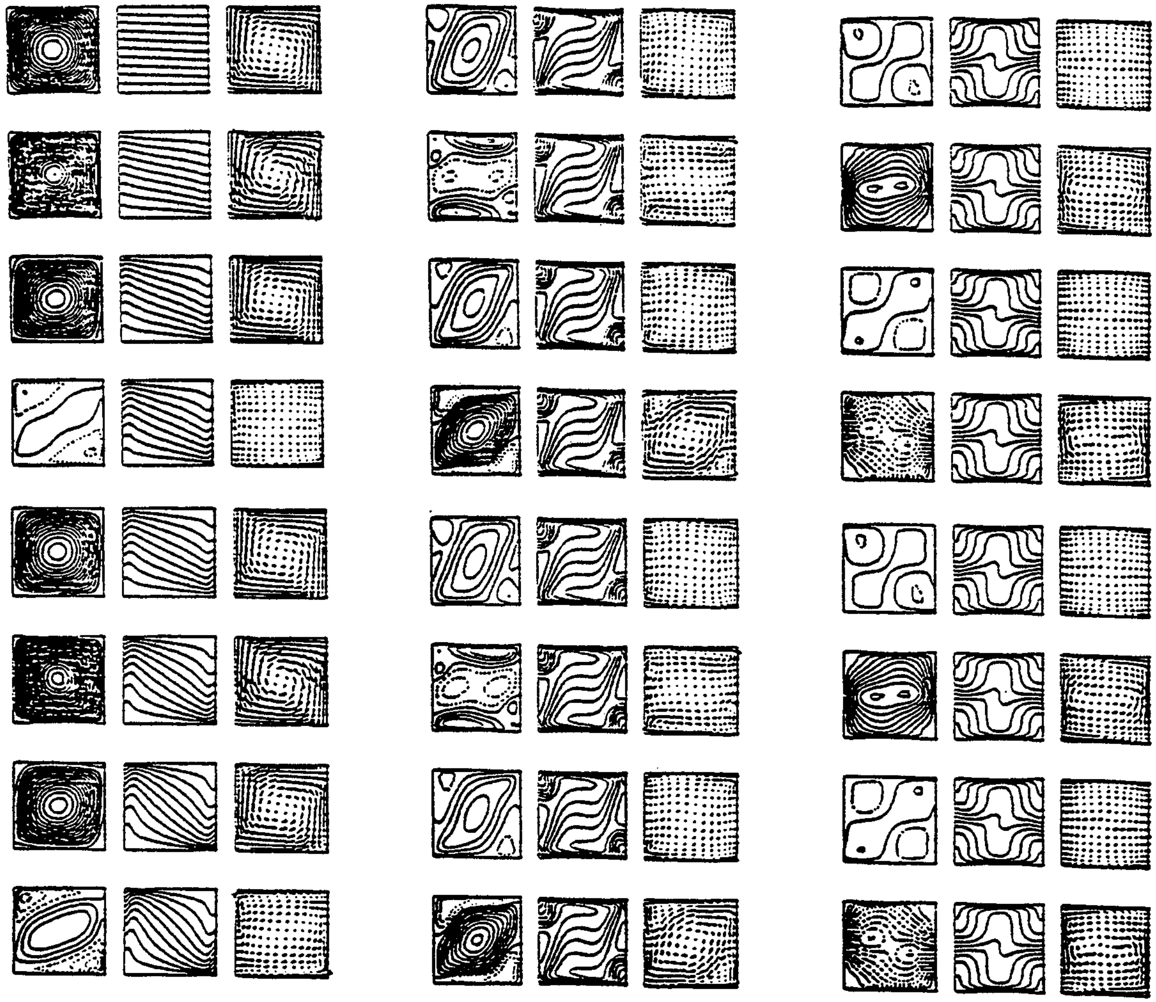


Fig. 4. Time Variation of Nusselt Number at Different Frequencies



(a) (b) (c)

Fig. 5. Stream Functions and Isotherms of High Frequency Vibration Convection

CONCLUSIONS & RECOMMENDATIONS

The following conclusions were obtained from the literature search and review: extensive effort in vibration convection study has been conducted for the past few decades; results indicate strong effects of vibration on convection, especially at reduced gravity; a time-averaged method has been developed and used extensively in the study of vibration convection at high frequencies.

From a numerical simulation of vibration convection in an enclosure, it was concluded that: different type of flow regimes exists for different vibration frequencies; a resonance regime exists with enhanced heat and mass transfer; the fluid flow approaches an asymptote at high vibration frequencies.

Results of this study strongly support the findings of other researchers. To assess the impact of vibration on crystal growth on orbit, quantitative information would be needed. It is recommended that further studies be conducted covering a wider range of Grashof number; that properties of a typical liquid metal be used; and that non-zero residual gravity be added. This will not only provide better understanding of the behavior of liquid melt in space but also provide necessary guidelines for the planning of ground experiments. Theoretical studies of the resonance phenomenon will also add to our understanding of this interesting and complex phenomenon.

REFERENCES

1. Richardson, P.D., "Effects of Sound and Vibration on Heat Transfer," Applied Physics Review, Vol. 20, 201-217, March, 1967.

2. Pak, H.Y., Winter, E.R.F., and Schoenals, R.J., " Convection Heat Transfer in a Contained Fluid Subject to Vibration," In *Augmentation of Convective Heat and Mass Transfer,* edited by A.E. Bergles and A.L. Webb, ASME, New York,. 158, 1970.

3. Gebhart, B., "Random Convection Under Conditions of Weightlessness," AIAA Journal, Vol. 1, 380-383, 1963.

4. Forbes, R.E., Carley, C.T., and Bell, C.J., "Vibration Effects on Convective Heat Transfer in Enclosures," Journal of Heat Transfer, Vol. 92, Ser. C, .429-438, March 1970.

5. Gershuni G.Z., Zhukhoviskii, E.M., and Yurkov, I.S., " On Convective Stability in the Presence of a Periodically Varying Parameter," PMM, Vol. 34, 470-480, 1970.

6. Gresho, P.M., and Sani, R.L., "The Effect of Gravity Modulation on the Stability of Heated Fluid Layers," Journal of Fluid Mechanics, Vol. 40, 783-806, June 1970.

7. Donnelly, R.J., Reif, F., and Suhl, H., "Enhancement of Hydrodynamic Stability by Modulation," Physical Review Letters, Vol. 9, 363-364, March 1962.

8. Kezios, S.P. and Prasanna, K.V., "Effect of Vibration on Heat Transfer from a Cylinder in Normal Flow," ASME Paper 66-WA/HT-43, 1966.

9. Bloor, M.S., "The Transition in the Wake of a Circular Cylinder," Journal of Fluid Mechanics, Vol. 19, 290-301, February 1964.

10. Carruthers, J.R., "Crystal Growth from the Melt," In *Treatise on Solid State Chemistry*, Vol. 5, 325-406, edited by N.B. Hannay, Plenum Press, New York 1975.

11. Zenkovskaya, G.Z. and I.B. Simonenko, "Effect of High Frequency Vibration on Convection Initiation," Izv. AN SSSR, Mech. Zhidk. Gaza 1(5), 51-55, 1966.

12. Gershuni G.Z., Zhukhoviskii, E.M., and Yurkov, Y.S., " Vibration Thermal Convection in a Rectangular Cavity," Izv. AN SSSR, Mech. Zhidk. Gaza 4, 94-99, 1982.

13. Sharifulin, A.N., "Supercritical Vibration-Induced Thermal Convection in a Cylindrical Cavity," Fluid Mechanics - Sov. Res. 15(2), 335-338, 1986.

14. Siraev, R.R., "Vibration Thermal Convection about a Uniformly Heated Cylinder," Izv. AN SSSR, Mech. Zhidk. Gaza, No. 3, 23-26, 1989.

15. Gershuni G.Z., Zhukhoviskii, E.M., *Convective Stability of Incompressible Fluids*, 1976.

16. Gershuni G.Z., Zhukhoviskii, E.M., A. Napomniashi, *Stability of Convective Flows*, Nauka, Moscow, 1989.

17. Zavarykin, M.P., S.V. Zorin, and G.F. Putin, "Experimental Study of Vibrational Convection," Dokl. Akad. Nauk SSSR, 281, 815-816, 1985.

18. Zavarykin, M.P., S.V. Zorin, and G.F. Putin, " Convective Instability in a Vibrational Field," Dokl. Akad. Nauk SSSR, 299, 309-312, 1988.

19. Ivanova, A.A., and Kozlov, V.G., "Vibrationally Gravitational Convection in a Horizontal Cylindrical Layer," Heat Transfer-Sov. Res. 20, 235-247, 1988.

20. Ivanova, A.A., "Influence of Vibrations of the Unsteady-State Convective Heat Transfer in a Cylindrical Cavity," Heat Transfer-Sov. Res. 20, 248-251, 1988.

21. Yurkov, Yu.S., "Vibration-Induced Thermal Convection in a Square Cavity in Weightlessness at Arbitrary Frequencies," In *II Vsesoyyuznyye seminor po gidromekhanike i teplomassoobmenu V nevesomosti* [Tezisy dokladov], Perm, 36-37, 1981.

22. Yurkov, Yu.S., "Vibration-Induced Thermal Convection in a Square Cavity in Weightlessness (Finite Frequencies)" In *Konvektivnyye techeniya,* Convective Perm Teachers' Institute, Perm, . 98-103, 1981.

23. Biringen, S. and Danabasoglu, G., "Computation of Convective Flow with Gravity Modulation in Rectangular Cavity," J. Thermophys. 4, 357-365, 1990.

24. Fu, W.S., and Shieh, W.J., " A Study of Thermal Convection in an Enclosure Induced Simultaneously by Gravity and Vibration," Intl. J. Heat Mass Transfer, 35, 7, 1695-1710, 1992.

25. Gershuni G.Z., Zhukhoviskii, E.M., "Vibration-Induced Thermal Convection in Weightlessness," Fluid Mechanics-Soviet Research, 15, 1, Jan/Feb, 1986. Translation from Gidromekhanika i Protsessy Perensa v Nevesomosti, 86-105, 1983.