High frequency vibration influence on heat transfer

T.P. Lyubimova, A Lizée, G.Z. Gershuni, D.V. Lyubimov, G. Chen, M. Wadih, B. Roux

HIGH FREQUENCY VIBRATIONS INFLUENCE ON HEAT TRANSFER

T.P. Lyubimova, A. Lizee*, G.Z. Gershuni**, D.V. Lyubimov**, G.Chen*, M.Wadih* and B.Roux*

Institute of Continuous Media Mechanics UB RAS, 614061 Perm, Russia
*Institut de Mécanique des Fluides, 1 rue Honnorat,13003 Marseille, France
**Perm State University, 15, Bukirev Street, 614600 Perm, Russia

Abstract - The effect of high frequency vibration on the flow and temperature fields is studied numerically for two configurations: a two-dimensional square cavity and an axisymmetrical liquid zone, subjected to an external temperature gradient. The mean fields of velocity and temperature are determined by means of a finite-element method and a finite-difference method, respectively. The characteristics of the flow and heat transfer are found to be strongly dependent on the vibrational parameters.

1 INTRODUCTION

High frequency vibrations have an influence to control the flow regimes and internal temperature fields in fluids subjected to an external temperature gradient (see, for example [1]). These vibrations play different role depending whether the cavity is totally filled with the fluid or whether the fluid has a free surface. In the present paper we study the effect of high frequency vibrations on heat transfer for two configurations.

The first one is a two-dimensional square cavity completely filled with a fluid. All the boundaries are rigid. The vertical walls are isothermal and maintained at different fixed temperatures; while the horizontal walls are thermally insulated. The axis of the high frequency vibration is oriented at an arbitrary angle θ with respect to the external temperature gradient. Here, a static gravitational field is taken into account, driving a thermogravitational convection. Then, it is interesting to consider the control of this thermogravitational convection by another mechanism of excitation (the thermovibrational one).

The second configuration is an axisymmetrical liquid bridge with a free surface heated by a radiating ring heater. Here, there is a substantial difference from the previous case due to the existence of a free surface. This system is described by utilizing the new approach developed in [2]. In this case

three mechanisms of mean flow generation by vibrations are active. Two of them are isothermal ones which are related to the existence of dynamical skin-layers near the rigid and free boundaries. The third one is the volumetric thermovibrational mechanism of the first order with respect to the Boussinesq parameter. We study the coupled effect of all these vibrational mechanisms in the absence of any non-vibrational flows (i.e., assuming zero gravity conditions and no thermocapillary effect). Vibration-driven surface streaming flow in a liquid bridge was studied experimentally in [3]. The role of isothermal vibrational mechanisms of the steady streaming related to the existence of the boundary layers near the rigid and free surfaces was investigated theoretically in [4].

2 GOVERNING EQUATIONS AND BOUNDARY CONDITIONS

2.1 Governing Equations

Let us consider vibrational convective flows under the following assumptions:
a) the vibration frequencies are so high that the dynamical skin-layer thickness δ is small in comparison with the characteristic length L:

$$\delta = (\nu/\omega)^{1/2} \ll L$$

b) on the other hand, the frequencies are non-acoustic so isothermal compressibility effects are not important:

$$\lambda = \frac{2\pi c}{\omega} \gg L$$

where (λ is the acoustic wave length, c is the sound velocity);
c) the characteristic amplitude of the vibrations is sufficiently small.

Under the above conditions the flow induced by vibrations can be decomposed into a pulsating component and a component averaged over a time scale large in comparison with the vibrational period. Then, the averaging method can be effectively applied. In the general case the isothermal pulsating velocity field is non-uniform and the accelerations of liquid elements are large in any reference frame. Then, as it was shown in [5], the temperature dependence of density should be taken into account not only in the body forces as in the conventional Boussinesq approximation but also in the inertia terms of the fluid motion equation: $\rho\partial\vec{v}/\partial t + \rho(\vec{v}\nabla)\vec{v}$. The governing equations for mean and pulsating fields obtained in this way for weak non-isothermal conditions ($\beta\Theta \ll 1$) are [5]:

$$\frac{\partial\vec{u}}{\partial t} + (\vec{u}\nabla)\vec{u} - b^2\omega^2\beta|W|^2\nabla T = -\frac{1}{\rho_0}\nabla p + \nu\Delta\vec{u} + g\beta T\vec{\gamma} \tag{2.1}$$

$$\frac{\partial T}{\partial t} + \vec{u}\nabla T = \chi\Delta T, \quad div\ \vec{u} = 0. \tag{2.2}$$

$$curl\ \vec{W} = 0, \quad div\ \vec{W} = 0 \tag{2.3}$$

Here $\vec{u}$ is the time-averaged velocity, $\vec{W}$ is the non-dimensional complex amplitude of the pulsating velocity field related to the pulsating velocity in the laboratory reference frame v_p by the expression:

$$\vec{v}_p = b\omega(\vec{W}exp(i\omega t) + \vec{W}^* exp(-i\omega t));$$

the other notation is conventional.

In some particular cases the isothermal pulsating velocity field is spatially uniform. This is, for instance, the case of a container with rigid walls completely filled with fluid and subject to the oscillations without change of container orientation. As it is shown in [5], in these cases we need to take into account quantities of the first order with respect to the parameter $\beta\Theta$ in the pulsating field; then the equations for vibrational convection take the following form:

$$\frac{\partial \vec{u}}{\partial t} + (\vec{u}\nabla)\vec{u} - \frac{1}{2}b^2\omega^2\beta V_n \nabla T = -\frac{1}{\rho_0}\nabla p + \nu\Delta\vec{u} + g\beta T\vec{\gamma} \tag{2.4}$$

$$\frac{\partial T}{\partial t} + \vec{u}\nabla T = \chi\Delta T, \quad div\ \vec{u} = 0. \tag{2.5}$$

$$curl\ \vec{V} = \beta\vec{n} \times \nabla T, \quad div\ \vec{V} = 0 \tag{2.6}$$

where $\vec{n}$ is the unit vector along vibrations axis, $\vec{V}$ is non-dimensional pulsating velocity amplitude in the reference frame connected with the vibrating container.

The equations (2.4)-(2.6) are exactly equivalent to the conventional equations of thermovibrational convection (see, [6,1]). The difference is in the normalization of the pressure.
The main difference in the new equations (2.1)-(2.3) from the conventional equations (2.4)-(2.6) is the quadratic dependence of the "vibrational force" on Boussinesq parameter: $\epsilon = \beta\Theta$. Indeed, the vibrational term in (2.1) is proportional to ϵ, and proportional to W^2 which is independent of ϵ. The vibrational term in (2.4) is proportional to ϵ, and to V_n which in turn is proportional to ϵ due to (2.6); giving rise to the quadratic dependence on ϵ.

2.2 Boundary conditions

Let us discuss the boundary conditions for mean and pulsating components on rigid and free boundaries. On rigid boundaries the normal components of the mean and the pulsating velocities should vanish. We should not impose any conditions for the tangential components of the pulsating velocity because of the lowering of order of the equations order for the pulsations.

In the general case, it is shown in [5] that when the pulsating velocity field is non-uniform, the generation of the time-averaged vorticity in the dynamical skin-layers near the rigid surfaces becomes important. This can be described with the help of an effective boundary condition of the Schlichting's type. If the tangential component of the pulsating velocity $\vec{v}_{pt}$ in the proper reference frame of the considered boundary domain is represented in the form:

$$\vec{v}_{pt} = \vec{V}_1 cos\omega t + \vec{V}_2 sin\omega t;$$

then the condition for the tangential components of the time-averaged velocity on the rigid surface $\vec{u}_t$ is formulated in the form [7]:

$$\vec{u}_t = -\frac{1}{4\omega}(2\vec{V}_1 div\vec{V}_1 + 2\vec{V}_2 div\vec{V}_2 + (\vec{V}_1\nabla)\vec{V}_1 + (\vec{V}_2\nabla)\vec{V}_2 + 3\vec{V}_2 div\vec{V}_1 - 3\vec{V}_1 div\vec{V}_2) \qquad (2.7)$$

where all the derivatives are taken along the boundary.

In the particular cases mentioned above, when the isothermal pulsating velocity field is uniform, the no-slip condition should be accepted for the time-averaged velocity on the rigid boundaries.

The boundary conditions for the mean and pulsating fields on a free surface will be discussed in detail in the Section 4 which is devoted to the investigation of vibrational effects on an axisymmetrical liquid bridge.

3 DIFFERENTIALLY HEATED SQUARE CAVITY

3.1 Problem definition

We consider first the case of a square cavity with rigid walls completely filled with the fluid. The cavity is subjected to a linear high frequency vibration. We consider different orientations of the vibration which are characterized by the angle θ between vibration axis and horizontal direction: (the case $\theta = 0$ corresponds to horizontal axis of vibration, the case $\theta = \pi/2$ - to vertical direction of vibration axis). The schematic description of the problem, including the boundary conditions and the coordinate system are given in *Fig.*1. The condition $\vec{u} = 0$ corresponds to the no-slip condition for the mean flow velocity; while the condition $f = 0$ is applied to the streamfunction f associated with the pulsating velocity $\vec{V}$ which satisfies $div\ \vec{V} = 0$.

The two vertical walls of the cavity are maintained at different fixed temperatures: T_1 and T_2. The horizontal walls are adiabatic. Under such conditions thermogravitational convection develops

for any value of the temperature difference $\Theta = T_1 - T_2$; the thermogravitational flow intensity depends on the Grashof number $Gr = g\beta\Theta L^3/\nu^2$ and the Prandtl number $\mathrm{Pr} = \nu/\chi$. We also use the Rayleigh number, $Ra = GrPr$.

In the situation discussed above the thermovibrational convection of the second order with respect to the Boussinesq parameter $\beta\Theta$ is the only vibrational mechanism of mean flow generation. Then, the equations (2.4)-(2.6) can be applied with no-slip conditions for the mean velocity on rigid boundaries. Here the intensity of the vibrational convection depends on the vibrational Rayleigh number $Ra_{v2} = (\beta\Theta b\omega L)^2/2\nu\chi$, where L is the dimension of the square cavity.

3.2 Results and discussion

Numerical computations have been performed with a finite element method using quadrilateral elements (9 nodes for velocity, temperature and amplitude of pulsating velocity; and 4 nodes for pressure). An implicit Euler scheme was used to solve the non-steady equations (transient problem); an iterative Newton-Raphson method was used to solve the non-linear system at each step of time.

The results of the calculations correspond to stationary solutions. They are shown for one set of values of Ra and Pr ($Ra = 10^4$ and $Pr = 0.71$). First, the calculations were done in the absence of vibrations ($Ra_{v2} = 0$); the corresponding isotherms are shown in $Fig.2(a)$. Then, the calculations were done for $Ra_{v2} = 10^5$ and for different directions of the vibration axis. $Figs.2(b-e)$ compare the form of the isotherms for four values of the vibration angle: $\theta = 0$, $\theta = \pi/4$, $\theta = \pi/2$ and $\theta = 3\pi/4$. We can see that vibrating the system tends to cause the isotherms to be oriented in the direction perpendicular to the axis of vibration. This effect for thermovibrational convection was pointed out for the first time in our previous paper [8]. Thus, the global effect of vibrations depends strongly on the direction of these vibrations with respect to the external temperature gradient. For $\theta = 0$, when both directions (vibration axis and external temperature gradient) are horizontal, vibration tends to promote vertical isotherms (i.e., a pure conduction regime) and so, tends to damp the convective flow. On the contrary, for $\theta = \pi/2$ when the vibration axis is perpendicular to the external temperature gradient, the deviation of isotherms from the vertical is increased and the kinetic energy of the flow is stronger (see Table 1).

Table 1 presents the values of the Nusselt number and the kinetic energy for the four different angles of vibrations. It is noteworthy that for horizontal vibrations ($\theta = 0$) the Nusselt number is very close to one and the kinetic energy to zero.

This result can be compared to that of [1] where it is shown that when the direction of vibration is parallel to the direction of temperature gradient the system is unconditionally stable in a weightlessness condition, i.e., zero gravity. So it is possible to suppress the effect of thermogravitational convection, when the vibrational force is sufficiently large.

	without vibrations	with vibrations			
		$\theta = 0$	$\theta = \pi/4$	$\theta = \pi/2$	$\theta = 3\pi/4$
Nu	2.244	1.041	2.144	2.493	1.318
Ec	64.82	1.26	50.02	122.07	8.95

Table 1: Values of Nusselt number and kinetic energy for different angles of vibrations ($Ra = 10^4$, $Pr = 0.71$ and $Ra_{v2} = 10^5$).

4 HEATED LIQUID BRIDGE WITH AXIAL VIBRATIONS

Different approaches with increasing complexity have been proposed during the last two years for solving the problem of vibrational convection inside a radially heated liquid bridge subjected to axial vibrations. Previously we studied vibrational convection in a cylindrical liquid bridge with a non-deformable free-suface by using a conventional approach (eqs. (2.4)-(2.6), [8]); in this case the effect of vibrations on the thermocapillary flow was also considered. More recently, the same problem was considered in the framework of the new approach developed in [5] (eqs.(2.1)-(2.3), [9]); the volumetric thermovibrational convective effect of the first order with respect to the Boussinesq parameter was studied as well as the time-averaged vibrational flow of Schlichting origin, i.e., due to the generation of the time-averaged vorticity in the skin-layers near the rigid surfaces. The influence of vibrations on the free surface shape and the effect of the free surface deformation on the mean flow structure was investigated in [10]. In the present paper, vibrational flows in a liquid bridge are studied taking into account the generation of the time-averaged vorticity near both the rigid and the free surface.

4.1 Problem definition

Let us consider an axisymmetric liquid bridge between two rigid rods separated by a distance $2h$ (*Fig.3*). The wetting lines coincide with the rods edges. The entire system oscillates in the axial direction with the displacement amplitude b and angular frequency ω.

The rods at $z = \pm h$ are assumed to be isothermal:

$$T = T_m \tag{4.1}$$

but the liquid bridge is heated by a ring heater. The thermal boundary condition on the free surface corresponds to heat exchange with the ring heater:

$$\frac{\partial T}{\partial n} = -\epsilon(T - T_a), \tag{4.2}$$

were ϵ is the effective heat exchange coefficient, T_a is the ambient temperature. The dependence of the latter on the axial coordinate contains the effect of the presence of the ring heater:

$$T_a(z) = T_m + \Theta \exp(-z^2/d^2). \tag{4.3}$$

Gravitational and thermocapillary effects are not considered.

4.2 Governing equations and boundary conditions

For weak non-isothermal conditions, the case being considered, the system of equations (2.1)-(2.3) are appropriate to study the vibrational flows.

We are interested in axisymmetrical solutions for which the non-zero components of the pulsating and mean velocities are the radial (W_r, u_r) and the axial (W_z, u_z) ones. In this case it is convenient to introduce a cylindrical coordinate system (r, z) with the origin at the symmetry center of the bridge.

For studying axisymmetric solutions it is convenient to introduce the stream-function and vorticity for the mean flow:

$$u_r = -\frac{1}{r}\frac{\partial \psi}{\partial z}, \quad u_z = \frac{1}{r}\frac{\partial \psi}{\partial r}, \quad \phi = -\frac{1}{r}(\frac{\partial^2 \psi}{\partial r^2} - \frac{1}{r}\frac{\partial \psi}{\partial r} + \frac{\partial^2 \psi}{\partial z^2}) \tag{4.4}$$

The equations (2.1)-(2.2) are rewritten for the considered configuration in terms of ψ and ϕ and take the form:

$$\frac{\partial \phi}{\partial t} + \frac{1}{r}(\frac{\partial \psi}{\partial r}\frac{\partial \phi}{\partial z} - \frac{\partial \psi}{\partial z}\frac{\partial \phi}{\partial r} + \frac{\phi}{r}\frac{\partial \psi}{\partial z}) + \frac{Ra_{v1}}{\mathrm{Pr}}(\frac{\partial E}{\partial r}\frac{\partial T}{\partial z} - \frac{\partial E}{\partial z}\frac{\partial T}{\partial r}) = \frac{\partial^2 \phi}{\partial r^2} + \frac{1}{r}\frac{\partial \phi}{\partial r} - \frac{\phi}{r^2} + \frac{\partial^2 \phi}{\partial z^2} \tag{4.5}$$

$$\frac{\partial T}{\partial t} + \frac{1}{r}(\frac{\partial \psi}{\partial r}\frac{\partial T}{\partial z} - \frac{\partial \psi}{\partial z}\frac{\partial T}{\partial r}) = \frac{1}{Pr}\Delta T, \quad with \quad E = |\vec{W}|^2 \tag{4.6}$$

The equation (2.3) for the pulsating velocity can be rewritten by introducing the potential of the

pulsating field connected with $\vec{W}$ by the relation $\vec{W} = \nabla\Phi$; i.e.:

$$\Delta\Phi = 0 \tag{4.7}$$

Let us discuss the boundary conditions. On the rigid boundaries at $z = \pm H$ the normal components of the mean and pulsating velocities should satisfy the conditions of impermeability:

$$\psi = 0, \quad \frac{\partial\Phi}{\partial z} = 1 \tag{4.8}$$

Taking into account the generation of mean vorticity in the dynamical skin-layers near the rigid surfaces we accept the condition of Schlichting's type on these surfaces. For the considered configuration this condition can be formulated in the form:

$$\frac{\partial\psi}{\partial z} = \frac{1}{4}Sc(3Re((1+i)\frac{\partial\Phi}{\partial r}\frac{\partial^2\Phi^*}{\partial r^2} + \frac{2}{r}\left|\frac{\partial\Phi}{\partial r}\right|^2), \tag{4.9}$$

where * denotes the complex conjugate quantity.

We do not impose any condition for the tangential components of the pulsating velocity on the rigid surfaces because of the lowering of the order of the equations for the pulsations.

The generation of the time-averaged vorticity takes place not only near the rigid surfaces but also near the free surface where capillary waves propagate from the vibrating rods. The dissipation of the surface wave energy is accompanied by the decrease of the waves momentum. Since the waves momentum is concentrated in a layer near the free surface, the momentum loss is balanced by the time-averaged viscous stress. Due to that, under this layer (near the free surface), vorticity should be generated which is of second order with respect to the waves amplitude. This phenomenon was investigated for the first time by Longuet-Higgins in [11]. We found that this effect can result in a strong mean flow near the free surface in the Czochralsky configuration [12]. This phenomena can be described with the help of an effective boundary condition for the mean shear rate on the free surface. We use the boundary conditions in the form given in [2,13], i.e., at $r = 1$ we accept:

$$\psi = 0, \quad \phi = Sc\ Im(\frac{\partial\zeta}{\partial z}\frac{\partial^2\Phi^*}{\partial z^2} - \frac{\partial\Phi^*}{\partial z}\frac{\partial^2\zeta}{\partial z^2}) \tag{4.10}$$

$$\zeta = \frac{\partial\Phi}{\partial r} - 2iS\frac{\partial^3\Phi}{\partial r\partial z^2} \tag{4.11}$$

$$\Phi = -2iS\frac{\partial^2\Phi}{\partial z^2} - \Sigma(\zeta + \frac{\partial^2\zeta}{\partial z^2}), \tag{4.12}$$

where ζ is the amplitude of the pulsations of the free surface (we do not take into account the effect of non-zero normal component of the mean velocity).

The thermal boundary conditions are:

$$T = 0 \quad at \quad z = H, \quad \frac{\partial T}{\partial r} = -Bi(T - T_a) \quad at \quad r = 1, \quad T_a(z) = \exp(-z^2/D^2). \tag{4.13}$$

The equations and boundary conditions are written in non-dimensional form; the value T_m is taken as the reference temperature. The values R, R^2/ν, ν, Θ are the scale factors for length, time, stream function and temperature respectively, where R is the mean radius of the liquid bridge. Here, $\Theta = T_a(0) - T_m$.

The problem is characterized by the following non-dimensional parameters: vibrational Rayleigh number $Ra_{v1} = \beta\Theta b^2\omega^2 R^2/4\nu\chi$, pulsating Reynolds number (or Schlichting parameter) $Sc = b^2\omega/\nu$, Prandtl number $\mathrm{Pr} = \nu/\chi$, Biot number $Bi = 4\epsilon\sigma * T_m^3 R_0/\chi$, parameters $\Sigma = \alpha/\omega^2 R^3$ and $S = \nu/\omega R^2$ which are responsible for capillary effects and viscous damping respectively, $D = d/R$ characterizing the heater length, and the aspect ratio $H = h/R$. Σ is the inverse of Weber number: $\Sigma = (We)^{-1}$.

4.3 Numerical Results

The problem for the determination of the pulsating field is separated from the determination of the mean components of hydrodymamical fields. For the solution of the problem for ζ and Φ the potential was represented as a sum of a linear function of z and axisymmetric eigenfunctions for an infinite liquid column. For this approximation of the potential the deviation of the free surface from its equilibrium position was found from the dynamical boundary condition taking into account the "stuck edge conditions" (i.e., the fluid sticks on the edges). This deviation was substituted into the kinematic condition, then the orthogonality relations on a free surface were employed. So, one obtains a non-homogeneous system of linear algebraic equations which can be solved by an iterative method. For the solution of the equations for the mean components, a finite difference method was applied.

The calculations were carried out at fixed values of Prandtl number, Biot number, aspect ratio and parameter D: $\mathrm{Pr} = 0.02$, $Bi = 2$, $H = 1$, $D = 0.5$. Parameters Ra_{v1}, Sc, Σ and S were varied.

Consider the results of the numerical study for the mean flows. In Figs.4(a-c) the streamlines of the

mean flows are presented for an isothermal situation (*i.e.*, $Ra_{v1} = 0$) at $Sc = 40$, § $= 5 \times 10^{-4}$ and for three different values of the parameter Σ ($a - \Sigma = 0.5 \times 10^{-3}$, $b - \Sigma = 10^{-3}$, $c - \Sigma = 3.5 \times 10^{-3}$). For such isothermal conditions the mean flow is generated by the coupled effect of the Schlichting and surface wave mechanisms. As one can see, the flow has a form of four vortices. The vortices located near free surface are induced by surface waves propagating along the free surface. The circulation in these vortices is such that the fluid moves along the free surface from the rigid rods.

Two symmetrical vortices located near the rigid rods are of Schlichting origin. In these vortices the fluid moves along the rigid surfaces in the direction opposite to that of the pulsating energy gradient; thus, in the lower part of the zone the circulation is clock-wise.

The vortices induced by the two previously discussed isothermal vibrational mechanisms have different directions of circulation and different locations; due to that they are well separated each from other. As one can see from Figs.4(a-c), the relative sizes and intensities of these vortices change with the change of parameter Σ.

The flow of pure thermovibrational origin (i.e., for $Sc = 0$) is shown in *Fig.*5) for $Ra_{v1} = 10^3$); it has the structure of two vortices with the same direction of circulation as that of the vortices induced by surface waves mechanism (and opposite to the direction of the Schlichting flow); i.e. in the lower part of bridge the circulation is counter-clock-wise.

In *Fig.*6 the structure of the flow caused by all the discussed vibrational mechanisms is presented for $Ra_{v1} = 10^3$, $Sc = 40$, $\Sigma = 3.5 \times 10^{-3}$ and $S = 5 \times 10^{-4}$. As one can see, the flow structure is close to the pure thermovibrational case (at these values of the parameters the intensity of the Schlichting flow is relatively small and the structure of mean flow generated by surface waves is nearly the same as that of thermovibrational flow).

An increase of the vibrational parameters leads to an increase of the mean flow intensity; the flow structure remains nearly the same.

Thus, there is a range of the parameters where the resulting flow has a form of two vortices with the directions of circulation opposite to that of the thermocapillary flow (in the case of normal thermocapillary effect). The location of these vortices coincides with that of thermocapillary vortices. This makes it possible to conclude that the vibrational mechanism can be effectively used for the suppression of thermocapillary flow. A detailed study is planned for the near future.

Vibrational flows of high enough intensity have a marked influence on the heat transfer. Our calcu-

lations show that the deformation of the temperature field by the vibrational flow is such that the lines of constant density are perpendicular to the vibration axis ($Figs.7(a-b)$). Thus, the effecf of high frequency vibrations on the heat transfer in a liquid bridge is similar to that observed in the case of a square cavity (see, $Fig.2(b)$). In $Figs.8(a-b)$, for sake of comparison, we display some previous results given in [8] for pure thermocapillary flows, for two values of Marangoni number ($Ma = 10$ and $Ma = 500$) where $Ma = \frac{|\partial\sigma/\partial T|\Theta R}{\rho\nu\chi}$. As one can see by comparing $Figs.7(a-b)$ and $Figs.8(a-b)$ the vibration effect is opposite to the thermocapillary one. Thus, in real technological experiments the effect of vibrations can result in the flattening of crystallization front.

5 CONCLUSIONS

The influence of high frequency vibrations on heat transfer has been studied for two different configurations.

In the case of a differentially heated cavity subjected to an horizontal temperature gradient, we have shown that the thermogravitational convection can be controlled by vibrations exerted in a selected direction. Vibration exerted in the direction' parallel to the external temperature gradient will damp thermogravitational convection.

In the case of a liquid bridge with a free surface maintained between two rods subjected to a radiative heat flux from a ring heater, three different vibrational mechanisms of mean flow generation are observed. Two of these mechanisms are isothermal ones, they are related to the dynamical skin-layers near the rigid and free surfaces; the third mechanism, non-isothermal one, is a volumetric thermovibrational mechanism. The latter is governed by the vibrational Rayleigh number linear with respect to the Boussinesq parameter. In the range of the parameters considered, coupling effect of the three vibrational mechanisms leads to a mean flow with a direction opposite to that of the thermocapillary one, thus providing a means of suppressing thermocapillary flow by high frequency vibrations.

For a more realistic description of a real floating zone system, it will be necessary to take into account convective flows of non-vibrational origin, like a thermogravitational flow ($g \neq 0$) and/or a thermocapillary flow. These extensions will be presented in a near future.

ACKNOWLEDGEMENTS

The present research was made possible in part by Grant MF 5000 from the International Science Foundation, and in part by supports from "Ministère de l'Enseignement Supérieur et de la

Recherche (réseau formation-recherche Franco-Russe) and from CNES (Division Microgravité).

REFERENCES

1. G.Z. Gershuni and E.M. Zhukhovitsky, Fluid Mech. - Soviet Res., 15, 63- (1986).

2. D.V. Lyubimov, Int. Workshop on Non-gravitational mechanisms of convection and heat/mass transfer. Zvenigorod, 1994, Abstracts, pp.18-19.

3. A.V.Anilkumar, R.N.Grugel, X.F.Shen, C.P.Lee and T.G.Wang. J. Appl. Phys., vol.73, N 9, pp.4165-4170 (1993).

4. J.A. Nicolas, D. Rivas and J.M. Vega. Int. Workshop on Non-Gravitational Mechanisms of Convection and Heat/Mass Transfer. Zvenigorod, 1994. Abstracts, p.14.

5. D.V., Lyubimov Microgravity Quarterly, Vol.4, n. 2 pp. 107-112 (1994).

6. S.M. Zenkovskaya and I.B. Simonenko, *Izv. AN SSSR, Mekh. zhidk. i gaza,* 5, pp. 51- 55 (1966).

7. G. Schlichting, Grenzschicht-Theory (Braun, Karlsruhe, 1951).

8. G.Z. Gershuni , T.P. Lyubimova, D.V. Lyubimov and B. Roux, ESA-SP-333, vol. 1, pp. 117-122 (1992).

9. G.Z. Gershuni , D.V. Lyubimov, T.P. Lyubimova and B. Roux, Microgravity Quarterly, vol. 4, n. 2, pp. 113-118 (1994).

10. G.Z. Gershuni , D.V. Lyubimov, T.P. Lyubimova and B. Roux, CRAS (1994); submitted for publication.

11. M.S. Longuet-Higgins, J. Acoust. Soc. Amer., 25, 60, pp.799 (1953).

12. V.G. Kozlov, D.V. Lyubimov, T.P. Lyubimova and B. Roux, Int. Workshop on Non-gravitational mechanisms of convection and heat/mass transfer. Zvenigorod, 1994, Abstracts, p.28.

13. D.V. Lyubimov, this issue.