Heat transfer due to high frequency vibration: a new approach for achieving thermally optimum geometry under microgravity conditions

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During recent years considerable effort has been directed towards the study of complex body forces whereby convective heat transfer rates might be increased. In natural convection, the interaction of non-homogeneities of density field with body force produces convective motion. Space related technologies have demanded a profound knowledge of these kinds of body forces; for example vibration, magnetic, etc which under earth condition are of second order importance.
The study of thermo-vibrational problems was originally inspired by its applications in cryogenic propellants in rocket system, Fashbaugh and Streeter [1]. This type of convection differs from natural convection induced by gravity in that it may be produced even under microgravity or space station conditions. The systematic study of this type of convection began in the early sixties, Schoenhals and Clark [2], and was later essentially focused on the mathematical aspect of body force modulation, for example see the review paper of Davis [3]. There, he emphasizes the importance of the relevant scales of the problem, and how it is possible to control the hydrodynamic stability of convective motion by proper tuning of modulation parameters.
The idea of using mechanical vibration as a mean for enhancing the heat transfer rate has also received equal attention from the early beginning. Forbes et al. [4] present an experimental study of the influence of vibration on heat transfer and fluid dynamic behavior of a differentially heated vertical slot. The direction of vibration is perpendicular to the temperature gradient. They find that there is a possibility of resonance, which leads to the heat transfer augmentation. This idea has been exploited in numerous papers [5-7] in which the geometry is a rectangular cavity. However, it should be pointed out that this idea is limited to the cases in which the thermal system possesses a natural frequency. This means that the external acceleration field should be thought as the superposition of a constant acceleration and a periodic acceleration with zero mean where the constant acceleration produces the natural motion in enclosure. Therefore, logically, for the system under the effect of periodic acceleration with zero mean there is no possibility of resonance.
The important issues related to the enhancement of heat transfer concern the type of thermal boundary conditions, relative orientation of vibration vector with the temperature gradient (non-parallelism) and the considered geometry. Here, we only review the papers under microgravity conditions in which the boundaries of enclosure are maintained at different but uniform temperatures and the direction of vibration is perpendicular to the temperature gradient. For other types of boundary conditions and vibrational direction, see Christov and Homsy [8] , Savino et al. [9] and Gershuni and Lyubimov [10].
Kamotani et al. [11] examine the influence of vibration with zero mean on the heat transfer behavior of the thermal system. Their results show that, in this case, vibration has no significant effect on the heat transfer rate. This finding may be explained by considering the range of frequency and amplitude used in that study; the amplitude and frequency were both very small.
The fundamental question that we address here is how to select the frequency and amplitude of vibration under microgravity in order to obtain optimal geometry for which heat transfer is maximized.
Of numerous possible combinations between amplitude and frequency of vibration, high frequency and small amplitude possesses particular characteristics, which make it attractive for heat transfer studies [10]. The most important of these characteristics is that it provides us with a closed system of equations governing mean field, which does not contain periodic coefficients.
Khallouf et al. [12] consider the influence of vibration on heat transfer and fluid flow behavior of the thermal system in the range of high frequency and small amplitude. Their study is limited to the case of a Prandtl number Pr = 1 and a vibrational Rayleigh number $Ra_v=10^5$ with the objective of studying the fluid flow structures. They propose the possibility of the heat transfer augmentation with respect to aspect ratios, A.

Our objective in this paper is to extend the result of [12] in the context of geometric optimization method, Bejan [13]. The governing equations under Boussinesq approximation, in a reference frame linked to the rectangular cavity, are written by adopting the time-averaged formulation [10]. The governing equations of the mean fields depend on three dimensionless parameters, namely Ra_v, Pr and the aspect ratio A. The relevant parameters considered are in the range of: $10^3 < Ra_v < 10^5$, $0.5 < Pr < 10$ and $1 < A < 5$. The typical fluid motion structures under microgravity conditions are obtained, as for example symmetrical four vortex-cell and a diagonal extended roll with strong intensity and two counter-rotative cells with weaker intensity.
By performing numerical experiments with a finite volume method, we have obtained power law correlation for Nusselt number, Nu, for each aspect ratio A. Some of the results are presented in table 1:

$$Nu = C\, Ra_v^{m}\, Pr^{n}$$

A	*C*	*m*	*n*
1	*0.07*	*0.3*	*0.01*
2	*0.001*	*0.5*	*0.02*
3	*0.001*	*0.7*	*0.02*
4	*0.0002*	*0.9*	*0.02*

Table 1

It should be noted that, we have also studied the evolution of the Nusselt number as a function of the Prandtl number. Our results show that for Pr >3, there is no significant influence on the Nusselt number.
In addition, we have presented a correlation, which provides optimum configuration maximizing heat transfer:

$$A_{opt} = 0.04 \frac{Ra_v^{0.4}}{Pr^{0.005}}$$

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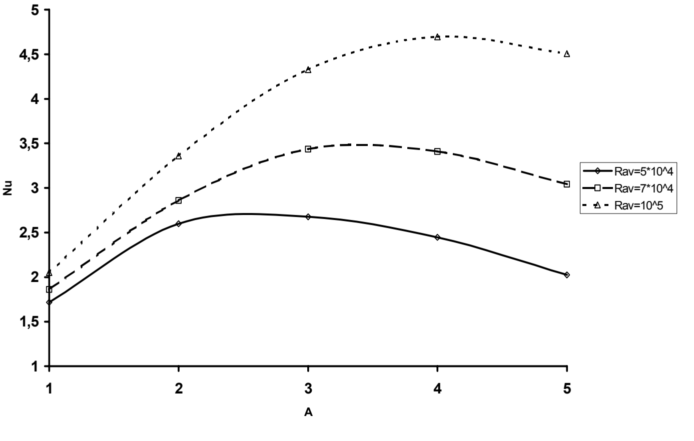

Figure 1. *Variation of de Nusselt number as a function of aspect ratio A for Pr =1 and different values of* Ra_v