NUMERICAL STUDIES OF FLUID FLOW IN MICROGRAVITY CONDITIONS FOR CONFINED CRYSTAL GROWTH

XAVIER RUIZ
Laboratori de Física Aplicada, Universitat Rovira i Virgili, Pza. Imperial Tarraco 1, 43005 Tarragona, Spain

LAUREANO RAMÍREZ-PISCINA
Departament de Física Aplicada, Universitat Politècnica de Catalunya, Avda. Gregorio Marañón 44, E-08028 Barcelona, Spain

JAUME CASADEMUNT
Departament d'Estructura i Constituents de la Matèria, Universitat de Barcelona, Avda. Diagonal 647, E-08028 Barcelona, Spain

Abstract. We study the convective flow induced by residual accelerations in microgravity conditions for different geometric arrangements which are relevant to crystal growth experiments. We consider both constant and oscillating acceleration and focus mostly on the transient relaxation dynamics. Results are relevant to estimate impact of more realistic residual accelerations in crystal growth experiments.

1. Introduction

Since the early Apollo, Apollo-Soyuz and Skylab programs, the impact of microgravity on confined crystal-growth systems from the liquid phase at high temperature has been subject of continuous interest. Since the microgravity environtment couples to the fluid flow through the presence of an effective, time-dependent acceleration field (g-jitter), big efforts like the OARE experiment or the HIRAP, SAMS and SAMS II systems, have been effected to obtain accurate and systematic characterization of that residual acceleration onboard orbiting spacecrafts. Three different and simultaneous contributions have been identified to date as sources of the acceleration field (Hamacher *et al.*, 1987; Nelson, 1991; Hamacher, 1996). The first one is the natural consequence of the orbital movement of the spacecraft (a noninertial reference frame). The second is the combination of external impulses or periodic disturbances generated by thruster firings, onboard machinery and crew activities. Finally, the excitation of the vibration modes of the spacecraft structure produces a broad band background of frequencies which is essentially stochastic in nature (Thomson *et al.*, 1995; Thomson *et al.*, 1997). As a previous step towards a deeper understanding of the impact of this rather complex time-dependent external forcing into cavity flow, we address here the numerical integration of the flow equations for relatively simple acceleration fields, namely constant and oscillatory. We

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study the response of the system to these forcings in differentially heated cavities of distinct geometries and boundary conditions and for material parameters which are directly relevant to actual experimental conditions. Our focus is on the response time scales and the structure of the emerging flow patterns. Although in many cases a stochastic modeling of the residual acceleration is indeed unavoidable, we expect that an accurate characterization of transient dynamics for different geometries and simple forcings may provide useful insights into the real problem.

2. Mathematical Formulation and Numerical Scheme

We have numerically integrated the transport equations in the Boussinesq-Oberbeck approximation under a (constant or oscilating) gravity $\mathbf{g}(t) = g_0\, f(t)\, \hat{\mathbf{n}}_g$, where $\hat{\mathbf{n}}_g$ is the unit vector in the direction of the effective gravity. We have considered a (2D) rectangular cavity with no-slip boundary conditions. The dimensionless equations read

$$\nabla \cdot \mathbf{v} = 0 \tag{1}$$

$$\frac{\partial \mathbf{v}}{\partial t} + \nabla \cdot \mathbf{v}\,\mathbf{v} = -\nabla p + \mathrm{Pr}\nabla^2 \mathbf{v} + \mathrm{Ra} \cdot \mathrm{Pr} \cdot f(t) \cdot \hat{n}_g \cdot \theta \tag{2}$$

$$\frac{\partial \theta}{\partial t} + \nabla \cdot \mathbf{v}\,\theta = \nabla^2 \theta \tag{3}$$

where $\mathbf{v}(\mathbf{r}, t)$ is the velocity field, $p(\mathbf{r}, t)$ and $\theta(\mathbf{r}, t)$ are the pressure and thermal fields respectively, and Pr and Ra are the Prandtl and Rayleigh numbers respectively.

The thermophysical properties of the liquid germanium have been used in the calculations and no thermal dependences of the different values have been considered. Consistently with available accelerometric data (Thomson *et al.*, 1997) we have used a realistic value of $g_0 = 1\, cm\, s^{-2}$ ($\cong 10^{-3} g_E$) for the gravity, with a range of frecuencies between 20 and 0.02 Hz in the oscillating cases. In all cases we have a maximum temperature difference of $\Delta T = 256$ K. We have used two cavities, a rectangular one of 3.2 cm $\times$0.8 cm (aspect ratio 4, Ra = 17745) and a square of 0.8 cm $\times$0.8 cm (Ra = 277.3). The corresponding Prandtl number is $\mathrm{Pr} = 7.15 \times 10^{-3}$. Owing to such a small value of the Prandtl number the thermal field is essentially decoupled from the velocity field and its relaxation to a steady state is much faster.

The different boundary conditions used lead to the three thermal profiles $\theta(x)$ shown in Figure 1 The so-called linear case corresponds to linear conditions in the upper and lower sides and fixed temperatures on the lateral sidewalls. In the so-called adiabatic case the upper and lower sides have adiabatic conditions in 1/4 of its length on the left, with the rest being at the same constant temperature than the

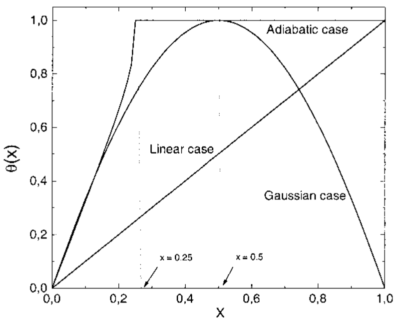

Figure 1. Thermal profiles for the three different configurations (see text).

right hand sidewall. The left hand side is at the other fixed temperature. In the third case, a Gaussian temperature profile is fixed on the upper and lower sides.

The integration of the PDE system and the corresponding set of boundary conditions has been carried out using standard structured finite volume procedures and a second order discretization scheme. The pseudo-explicit PISO algorithm has been used to couple the transport equations (STORM, 1998). The mesh refinement method has provided the most convenient number of mesh nodes taking into account both accuracy and computer time.

3. Results and Discussion

3.1. Steady flow modes

As limiting case of vibroconvective flow patterns, we have considered the steady flow modes when a constant gravity acts parallel to either x or y axes. In all cases we start from a quiescent state with constant temperature by setting all variables equal to zero and continue the numerical integration until the system reaches a steady state.

When the gravity acts parallel to the y axis the steady flow patterns are unicellular in the linear and adiabatic cases but bicellular when gaussian thermal conditions have been applied. The time spent in reaching the steady state has been of the order of one minute (a little bit longer for the linear case). Maximum horizontal velocities are of order of 1.5 and 2 mm s^{-1} in both linear and adiabatic boundary conditions, whereas in the gaussian case they where lower, nearly 1 mm s^{-1}. As can be seen in Figure 2 good mixing was obtained in the linear and gaussian cases, however in the adiabatic configuration, only one fourth of the cavity is dynamically active. Note finally that in the linear case, horizontal velocity profile in the center of the cavity agrees well with the asymptotic profile – the so-called Birikh-Haart profile (Thevenard and Ben Hadid, 1991; Thomson and Viñals, 1996) – expected in the limit of large aspect ratio.

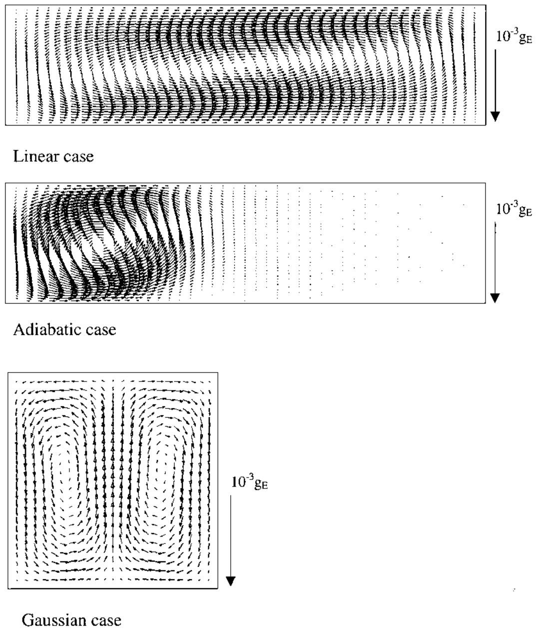

Figure 2. Steady flow modes for a constant **g** in the vertical direction in the three considered configurations.

If gravity acts parallel to the x axis, the two non equivalent configurations, with gravity acting in the opposed or in the same direction than the stablished thermal gradient, have been analyzed. In the linear case, the first configuration is always stable, whereas the second one (the well-known Rayleigh-Benard configuration) may be unstable depending on the Rayleigh number. For our set of parameters a final stable quiescent state is also reached in this second case after a relaxation time of roughly one minute. Figure 3 shows details of the dynamical field in three different points inside the cavity. In both the adiabatic and the gaussian cases the velocity field evolves to non-quiescent steady two-cellular patterns within a similar relaxation time scale. The maximum velocity is typically of order 1 mm s^{-1}.

3.2. VIBROCONVECTIVE FLOW

We have considered a sinusoidal oscillating gravity of frecuency Ω along the y direction. All computed cases reached a steady state consisting of an oscillatory flow mode that follows the external forcing (Thomson *et al.*, 1995). In the adiabatic case the vortical structure is basically confined to the adiabatic region. In the gaussian case, the oscillating pattern mimics the one obtained in the constant gravity case. In addition, in all three cases, for frequencies smaller than the one associated to the relaxation time of the system, the maximum velocity is basically independent of frequency, whereas for larger frequencies it strongly decreases with

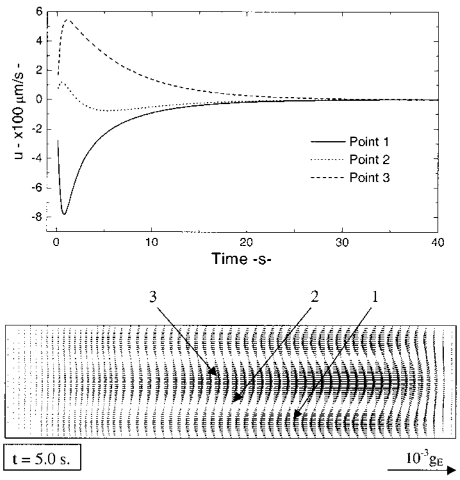

Figure 3. Transient evolution of the horizontal component of the velocity. A snapshot of the flow pattern is also shown.

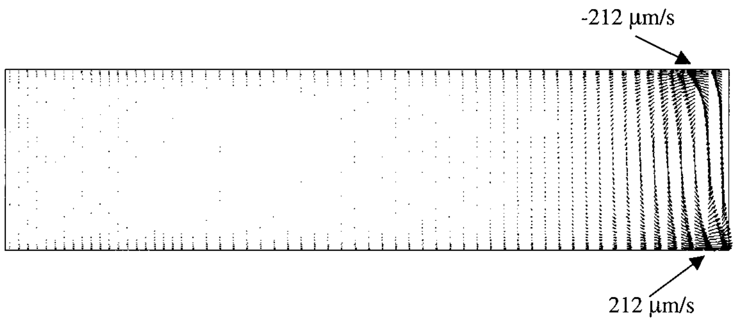

Figure 4. Snapshot of the flow mode during the transient in the oscillating case.

frequency. Noticeable oscillations of the thermal field have been observed for low frequencies. As a consequence of the fluid viscosity, different phase shifts between external forcing and actual velocities have been observed for different positions inside the liquid. In both linear and adiabatic cases a transient counterrotating vortical structure typically appears at the hot extremum in the initial stages (see Figure 4), which survives for longer times in the adiabatic case.

4. Conclusions

Convective flows induced by residual accelerations may significantly affect the performance of confined crystal growth experiments in microgravity. In this paper we have considered realistic cavities and material parameters, and we have numerically studied the transient and steady flow modes for both constant and oscillating gravity conditions. In all cases the time scales of transients are rather large compared to dominant frequencies of the acceleration field. For germanium, typical relaxation times for realistic microgravity conditions are of the order of 1 minute, and fluid velocities of the order of mm s^{-1}. The transient flows generated may be significant even in stable configurations with a quiescent asymptotic state. A more systematic study of the transient spatio-temporal response of these systems is clearly still necessary and may be useful for the more complicated and realistic case of a stochastic acceleration field.

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