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DEFORMATION OF FLUID COLUMN BY ACTION OF AXIAL VIBRATION AND SOME ASPECTS OF HIGH-RATE THERMOCAPILLARY CONVECTION

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ABSTRACT

The deformation of the fluid column by an action of a low-frequency vibration is considered. It is shown that behaviour of the free fluid surface depends from the frequency of applied vibration and its amplitude. In the area of very low frequencies when fluid has time to comment on travel of bounding solid walls limiting column the harmonical oscillations of free surface with given frequency are observed. With increase of vibration frequency the steady - state relief on free fluid surface is formed. If the amplitude of vibration is very small and the frequency corresponding to the first peak in the vibration spectrum on the Mir orbital station the deformation of free surface tends to zero. Fluid flow induced thermocapillary effect on deformed free surface is more unstable as in the case of smooth cylindrical surface. It was shown that width of heating zone affects very essentially on flow pattern and on transition to oscillatory regime of thermocapillary convection.

INTRODUCTION

A fluid column has been the subject of investigation over a long term of years. Currently these investigations had expanded still more in connection with necessities of space materials science, in particular of crystal growth by floating zone method. Complex process of crystal growth under action of vibrations set being aboard the spacecrafts and of thermocapillary convection has been broken up into two groups of problems which was solved earlier separately and by different methods. The problem of stability and deformation of fluid column under vibration was solved only for isothermal fluid by analytical methods. Thermocapillary convection and its effect on crystallization process were studied by numerical simulation and without vibration perturbations. Attempt to combine the both problems had been undertaken in (ref.1) using the known analitical solutions about fluid column deformation by action of axial vibration (refs. 2 and 3).

The undertaken investigation of complex problem, especially under action of frequencies set, and also the unexpected and conflicting results obtained in experiments during the SL - D1 and SL - D2 (ref. 4) have had a stimulating influence on beginning of this work.

From the outset presenting work had been planed so as to combine the both lines of investigations. In this connection, exact calculations of free surface deformation would be carried out with the help of the Navier - Stokes equations and a study of thermocapillary convection ought to be extended to the area of the high Marangoni numbers existing in real technological processes. The two circumstances favoured the realization of this plan:

- development of new finite-difference scheme of the third order of accuracy and of new very effective algorithm for numerical solution of the Navier-Stokes equations in velocity-pressure variables (ref. 5);
- obtaining of financial support of NASA allowed to purchase Pentium PC.

Presenting work is the first stage of plan having for an object to create a computer program for calculation of complex process of crystal growth by floating zone method with regard for deformation of free fluid surface on account of vibration, thermocapillary flow and control magnetic field (ref. 6).

OUTLINE

Consider the fluids flow in a circular cylindrical zone of height L and radius R with free sides surface. The temperature is constant. The cylinderes foots are oscillate in the axial direction. The fluid equations to be solved are the Navier-Stokes equation:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial r}+v\frac{\partial u}{\partial z}=-\frac{\partial p}{\partial r}+\nu\Big[\frac{\partial}{\partial r}\Big(\frac{1}{r}\frac{\partial (ru)}{\partial r}\Big)+\frac{\partial^2 u}{\partial z^2}\Big] \tag{1}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial r}+v\frac{\partial v}{\partial z}=-\frac{\partial p}{\partial z}++\nu\Big[\frac{1}{r}\frac{\partial}{\partial r}\Big(\frac{1}{r}\frac{\partial (rv)}{\partial r}\Big)+\frac{\partial^2 v}{\partial z^2}\Big]+Re_\omega \sin \Omega t \tag{2}$$

$$\frac{\partial u}{\partial r}+\frac{\partial v}{\partial z}+\frac{u}{r}=0 \tag{3}$$

where u,v are velocity components, p is pressure, ν is kinematic viscosity, $Re_\omega=\omega Ra/\nu$ is vibrational Reynolds number, a is amplitude of displase, $\Omega=\omega R^2/\nu$, ω is frequency of vibration, t is time. Fluid density has been normalised to unity. The equation system (1)-(3) is completed with boundary condition:

- on solid bodies ($z=0,L$) $\quad u=v=0$
- on the free fluid surface ($R=\xi(z)$) $\quad u=\partial\xi/\partial t$

  tangential viscous stresses are zero $\quad \partial v_n/\partial n+\partial v_s/\partial s=0$

  normal stresses $\quad p-2\partial v_n/\partial n-K_\sigma(R_1^{-1}+R_2^{-1})=0$

where n and s are normal and tangent to free surface respectively, $K_\sigma=\sigma R/\rho\nu^2$ is capillary constant, σ is surface tension. R_1 and R_2 are the principal radii of curvature.

In the preset work the basic idea of VOF method (Ref. 7) is adapted to solving above problem.

NUMERICAL RESULTS

<u>The deformation of free fluid surface.</u> The deformation of free fluid surface. The three different regimes of vibration had been considered. For the least frequency (Fig. 1) when fluid is able to respond to oscillations of solid ends such point on free fluid surface oscillates with frequency of applied force. This result agrees qualitatively with experiment (Ref. 8) and with the approximate analytical solutions (Refs. 2,3). Under more high frequency of vibration fluid in every point cannot - finish complete cycle of oscillations. As a result oscillations in every point on free surface decay (Fig. 2b). and steady - state relief is formed.For the first peak of vibration spectrum on the Mir orbital station (ref. 9) oscillations in every point on free fluid surface die out after transition from the vibration beginning. As an axample, the oscillations in point on free fluid surface with the coordinate z = L/4 had been presented in Fig. 3.

<u>Thermocapillary convection under the high Marangoni numbers.</u> It seems reasonable to say that vibration will have impact on stability of thermocapillary flow. Influence of free fluid surface form on temperature field and flow pattern under the large Marangoni numbers had been considered for case when deformation free fluid surface is held steady-state (Fig. 4).

Thermocapillary effect is characterized by kinematic condition on free fluid surface

$$\partial v_n/\partial n = MaPr^{-1}\partial\theta/\partial s$$

where $Ma=\gamma\Delta TL/\rho\nu a$ is the Marangoni number, $\Delta T=T_1-T_0$ is characteristic temperature difference, $\theta=(T-T_0)/\Delta T$, $\gamma=-\partial\sigma/\partial T$, $Pr=\nu/a$ is the Prandtl number.

A heating of fluid zone proceeds on the source side of free fluid surface in the form of exponential curve $\partial\theta/\partial r=A\exp(-B(z-L/2)^2)$ where A and B are selected constants.

Crystallization is imitated on the end z = 0 with impurity balance according to equation

$$\partial c/\partial z=-Sc(1-k_0)Re_{cr}c,$$

here $Sc = \nu/D$ is the Schmidt number, $Re_{cr} = v_{cr}L/\nu$ is dimensionless crystallization rate, k_0 is equilibrium coefficient of dopant distribution ($k_0 < 1$), c is concentration, D is diffusion coefficient; "s" falls into crystallization boundary.

Previously we found out physical cause of oscillatory regime advent for thermal gravitational convection, the Kelvin - Helmholz's instability (Ref. 10). Similar search for thermocapillary convection showed that one of cause inducing oscillations can be form of heat flux on free fluid surface. The wide zone of heating induces oscillatory regime of thermocapillary convection (Fig. 5b, where A = 0. 8, B = 0. 3) , whereas oscillations are absent under narrow zone of heating (Fig.5a, where A = 5, B = 15).

CONCLUDING REMARKS

Conducted investigation on vibration effect on fluid column gave quantitative configuration about high sensitivity of fluid column to vibrations especially in the area of low frequencies and for small-viscous fluids (semiconducting materials, for example). Unexpected phenomenon of steady-state relief formation on free fluid surface for vibrating column had been discavered. It is planned to carry out the series of the experiments on the Mir orbital space station for a verification of the obtained data.

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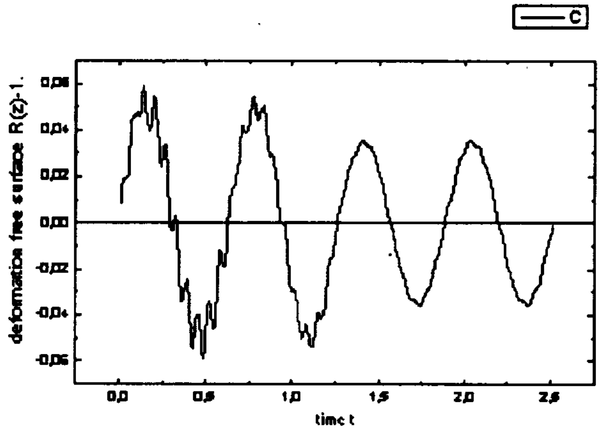
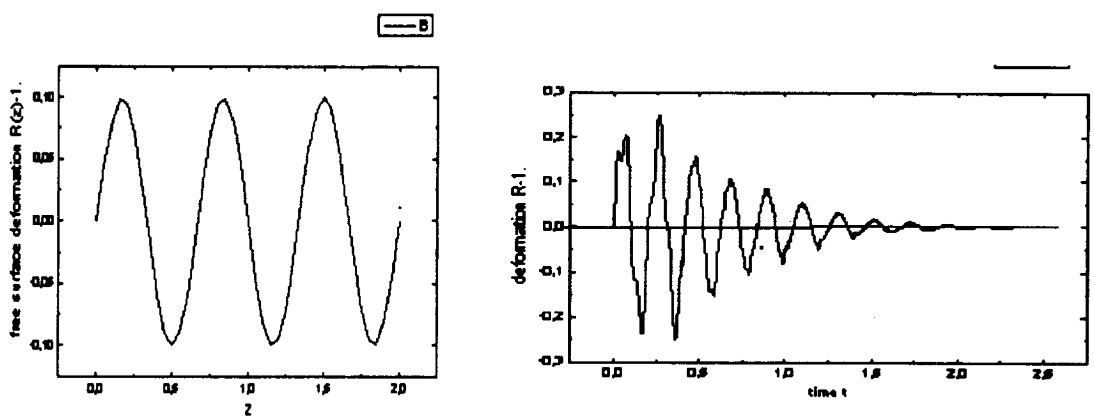


Fig.1. Free surface deformation at z = L/4 by Re_{ω} = 10.; L/R = 1.; Ω = 10.; K_{σ} = 3.26 10^3



a) b)

Fig 2. Shape (a) and deformation at z=L/8 (b) of free fluid surface by Re_{ω} = 30.; L/R = 2.; Ω = 30.; K_{σ} = 3.26 10^3

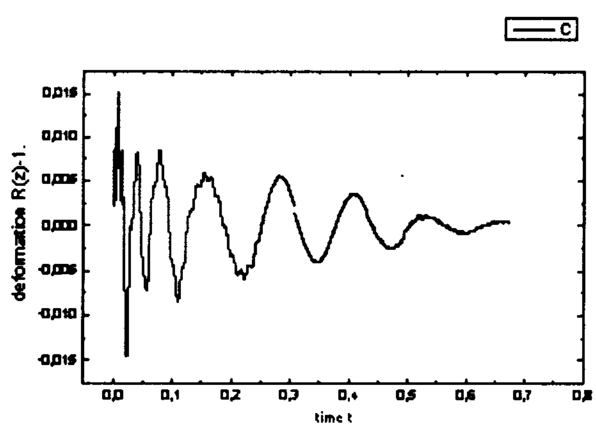


Fig. 3. Free surface shape at z = L/4 by Re_{ω} = 3.12.; L/R = 1.; Ω = 200.; K_{σ} = 3.26 10^3

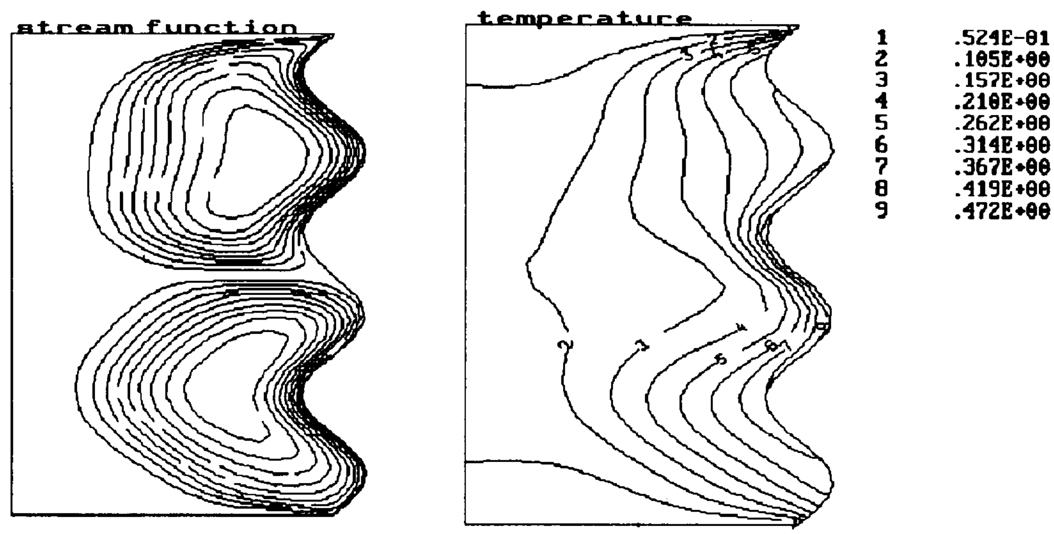
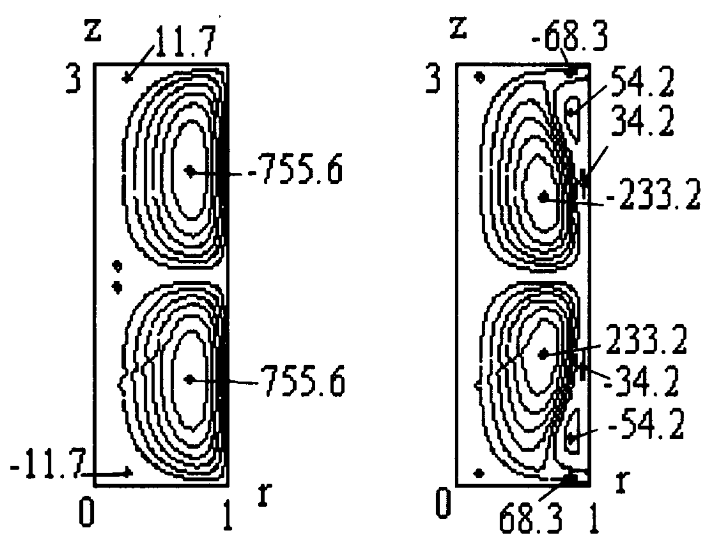


Fig. 4. Stream function and isotherms for goffred free fluid sirface similar to data in Fig. 2 by Ma=2600, Pr=0.018, A=3, B=10



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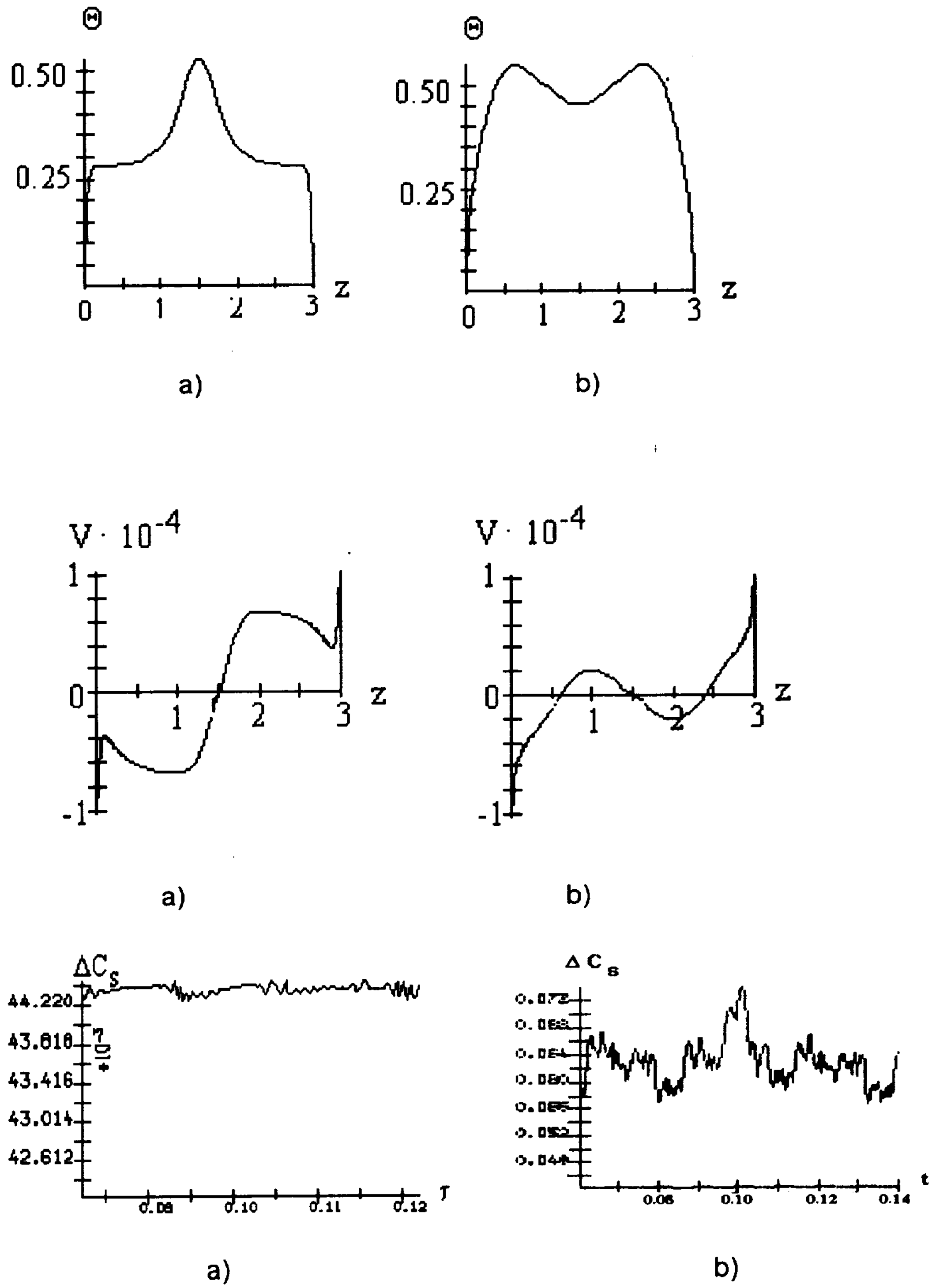

Fig. 5. Temperature distribution on free fluid surface ($r = 1$), stream function, distribution of velocity on free surface and impurity concentration difference on phase boundary ($z = 0$) for narrow (a) and wide (b) zones of heating . Ma = 5400 ; Pr = 0.018; Sc = 10; Re = 0.2; k = 0.023.

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