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Effect of axial vibration on free surface flows in cylindrical liquid*

Pan Xiu-Hong(潘秀宏) and Jin Wei-Qing(金蔚青)†

Shanghai Institute of Ceramics, Chinese Academy of Sciences, Shanghai 200050, *China*

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The influence of axial vibration on free surface flows in an open cylindrical container was studied by optical in situ observation method under isothermal conditions. This ground-based experiment was performed on an electromagnetic vibrator with oscillatory frequency of 100Hz. Water–glycerol mixture was chosen as the model liquid. Results showed that small amplitude ($< 100\mu$m) could generate a new type of steady streaming flows on a free surface, which were mainly driven by the combination of propagating surface wave and Stokes layer effect. The steady flow manifested various patterns according to the vibration amplitude level. Higher amplitude made steady flow periodical or turbulent, which could be characterized by the critical vibrational dimensionless Reynolds number $(Nr_e)_c$. The calculated value of $(Nr_e)_c$ was of the magnitude of $10^{-2} - 10^{-1}$. In addition, surface streaming velocities were measured by the particle scattering technique. It was found that the velocity increased parabolically with vibration amplitude and decreased with viscosity for a fixed flow pattern.

Keywords: vibration, convection, surface flow, in situ observation
PACC: 8110F, 9260E, 6800

1. Introduction

In crystal growth from liquid phases the convective flow has a significant influence on the mass and heat transfer, so how to control the convection is important for obtaining high-quality crystals. Using external forces to control melt convection and thus control crystal growth has been widely adopted. Magnetic fields,[1−3] rotations,[4,5] reduction of gravity,[6,7] and centrifugal and Coriolis forces,[8] are the typical techniques. Recently, it has been found that vibration can generate steady convective flows in melt and therefore can be used to control crystal growth. The effect of vibrations on the growth of crystals from some liquid phases has been studied by many authors.[9−13] They found the influence of vibrations on the characters of the crystallization and the crystal properties.

Vibration has been proven actually useful in crystal growth for it is able to influence the thermocapillary and buoyancy convections.[14,15] The driving mechanisms of vibration-induced mean flow and the solid–liquid interface inversion also have been discussed.[16,17]

However, most previous reports are mainly concerned with the vibrational bulk convection flows, neglecting the free surface distortion; only a few papers deal with the free surface distortion or the surface flow induced by vibration.[14,18] Furthermore, how such vibration-induced flows interact with natural convection is still not expounded. It is necessary to investigate further the motion of free surface streaming flows from a liquid phase subjected to vibration, especially for Floating-zone (Fz) and Czochralski (Cz) techniques.

In this paper, we study the free surface flows generated by vibrations in Czochralski-like configuration (without crystal rod) under isothermal conditions and discuss the influence of vibration parameters on them. It is expected to attain more detail information of vibrational effect on liquid phase, so as to improve crystal growth techniques.

2. Experiment

Free surface flows of an isothermal liquid phase in a cylindrical container subjected to an axial vibra-

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†Corresponding author: E-mail: Wqjin@sunm.shcnc.ac.cn

tion were considered. Water–glycerol mixture was selected as the model liquid with height h and diameter d (see Fig.1). Figure 2 is a schematic of the experimental setup used for generating and visualizing surface streaming flows as well as for measuring the surface flow velocities. An opaque cylindrical tube filled with the liquid mixture was fastened to an electromagnetic vibration machine (VIBRATOR-S, J. Morita Corp.). The orientation of the vibration was parallel to the gravitational acceleration. The vibration frequency f was set at 100Hz, with the vibration amplitude a being controlled by the input voltage V of the vibrator, monitored by a digital voltmeter with a resolution of 1V. The variation of a with V was tested using a laser vibration-meter, and the amplitude ranged from zero to 200±0.5μm. A thin layer of aluminium powder of 40μm in size on the free surface was used as tracer particles for flow visualization and velocity measurements. When the vibrator worked, the tube vibrated synchronously and made the liquid move. The surface flows were seen through a camera head (TK-1280E, colour video camera, CCD) just above the tube and then were recorded by a video recorder with the speed of 25 frames per second. An image processor (DVS-1000, Hamamatsu Photonics) was used between the CCD and the video recorder to visualize the trajectory of tracer particles clearly.

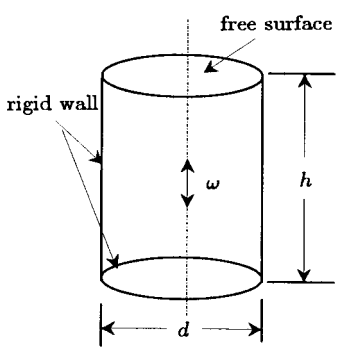


Fig.1. Scheme of the liquid phase.

The displacement of moving particles was measured using the image processor; the accuracy reached ±0.01cm. The particle velocities were measured near the centre of the free surface in order to avoid the influence of the high radial velocity gradients near the rigid wall of the container. In view of the different size and weight of different particles, we selected the highest velocity among a series of values measured as the flow velocity. The kinetic viscosity of the liquid η varied in the range of 1.0–15.0 centipoise (cp). The diameter of the tube was specified as 2.2cm and the aspect ratio $l = h/d$ was adjusted by the altitude h.

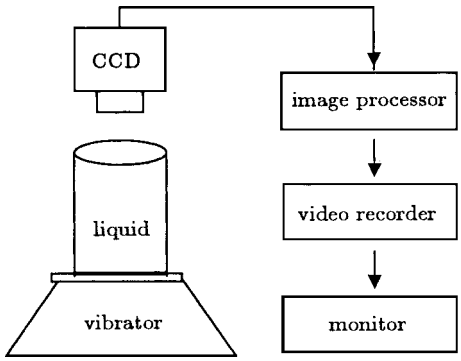


Fig.2. Schematic of the experimental arrangement.

3. Results and discussion

3.1. Effect of vibration on surface flow patterns

Experimental results showed that a small vibration amplitude (usually not greater than 100μm for the liquid investigated) could generate steady flows on free surface for the given vibration frequency. The amplitude varying intervals for steady flows were different for liquids with various physical parameters. Figure 3 shows a typical steady surface flow pattern. These images were taken for the liquid with aspect ratio l=3 and viscosity η=2cp. In this case, the amplitude varying interval for steady flow is approximately from 25 to 60μm. Free surface would keep standstill at amplitudes less than 25μm due to the viscous force (Fig.3(a)). Nevertheless, surface flow would become periodical or unsteady once the vibration amplitude was greater than 60μm. In crystal growth, unsteady convection is undesirable and should be avoided in all cases. However, in many cases steady convective flow is useful, so in our experiments, the study was focused mainly on steady surface flows.

The steady surface flows have various patterns at different amplitude levels. For the case mentioned above, the free surface took on a pattern of two symmetric toroidal flows (Fig.3(b)) in a large scope of amplitudes (from 25 to 50μm or so). One of these vortices circulated clockwise and the others rotated anticlockwise. In this scope, the increase of vibrational amplitude only augmented flow velocity while the flow structure remained unchanged. However, this type of steady flow would transfer into another new pattern as the amplitude became greater than 50μm (see Fig.3(c)). This flow structure was formed by four vor-

tices. In this case, the flow direction of two vortices was clockwise and that of the other two was reversed. Moreover, one vortex did not have the same circulative direction as its neighbours. Amplitudes higher than 56μm would generate high-velocity surface flows composed of eight vortices in total as shown in Fig.3(d). Similarly, only half of these vortices circulated in the same direction.

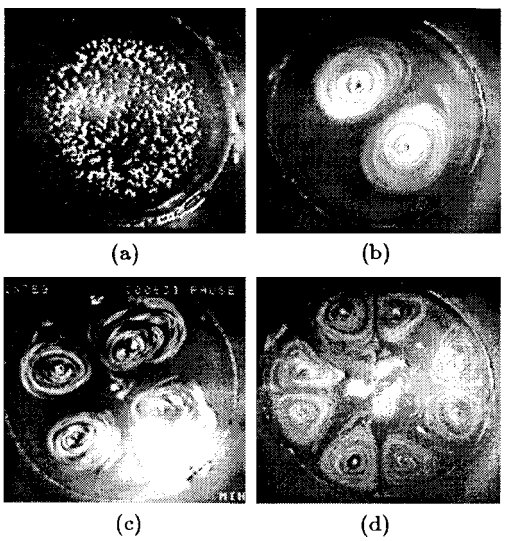


Fig.3. The variation of a typical steady surface flow pattern with amplitude. (η=2cp and l=3). (a) a=0, (b) a=48.8, (c) a=53.4, (d) a=56.6μm.

In our studies, the following inequalities are satisfied:

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

$$a \ll L.$$

Here $\nu = \eta/\rho$ is the kinematic viscosity, ρ is the density of liquid, $\omega = 2\pi f$ is the angular frequency of vibration, a is the displacement amplitude, and L is the characteristic size of the liquid.

In this case, the fluid motion can be decomposed into the mean and pulsating parts by the multi-scale method.[16] When the container vibrates, a thin Stokes layer is formed near the rigid surface where the pulsating vorticity differs from zero. The nonlinear interaction of this pulsating vorticity with the tangential non-uniformities of the pulsating velocity leads to the generation of mean vorticity, which can diffuse outside the skin-layer. According to the boundary layer theory, the above effect can be described with the help of effective boundary conditions for mean velocity at an outer edge of the boundary layer. This mean-flow generation by vibrations, due to the generation of mean vorticity in the dynamical skin-layers near the rigid vibrating boundaries, is called the Schiliching mechanism. The effect of the Schiliching mechanism can be characterized by the vibrational dimensionless Reynolds number, $Nr_e = a\omega^2/\nu$.

The generation of mean vorticity also takes place near the free surface, where the capillary waves propagate from the rigid walls. The wave effect can also be described as mean flows with the help of an effective boundary condition for the shear rate on the free surface. This mean-flow generation by the waves propagating along the free surface is called surface wave mechanism. This driving mechanism can be characterized by the vibrational dimensionless Weber number, $Nw_e = \rho\omega^2 L^3/\alpha$. Here α is the surface tension coefficient.

The dimensionless parameter characterizing the vibration amplitude is only the vibrational Reynolds number Nr_e, which has a simple physical sense: the ratio of inertial to viscous forces in a given flow. Too small a Nr_e value cannot make the liquid move. Only when the Reynolds number gets high enough, can surface flows be seen. Experiments also show that Nr_e has a critical value $(Nr_e)_c$: when $Nr_e > (Nr_e)_c$, the surface steady flows will transfer to unsteady ones. For a given vibration frequency, the value of $(Nr_e)_c$ can be calculated. It was found that the values of $(Nr_e)_c$ lie in the range of $10^{-2} - 10^{-1}$. The variation of $(Nr_e)_c$ with physical properties of the liquid is shown in Fig.4. S_c=ν/D is the dimensionless Schmidt number. Here D is the coefficient of diffusion. In our studies there was no heat transfer, so S_c is the only dimensionless parameter characterizing the inherent physical quality of the liquid. It represents the ratio of momentum transfer to mass transfer. Figure 4 indicates that not only the liquid properties but also the geometrical conditions can influence $(Nr_e)_c$ values.

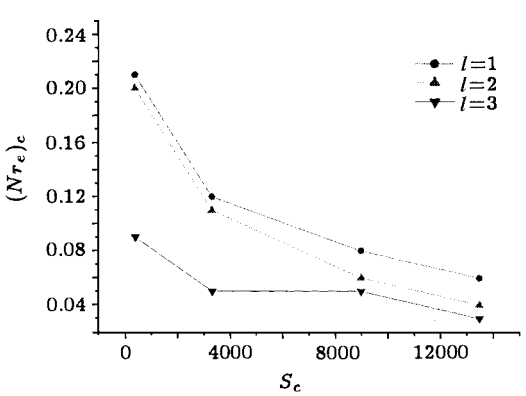


Fig.4. Calculated $(Nr_e)_c$ versus S_c for a constant vibration frequency. (S_c is the value of dimensionless Schmidt number).

At small amplitudes, the Schiliching mechanism is weak and the surface wave mechanism is the main flow-driven mechanism. Two symmetric vortices with large diameters appear near the free surface, along the free surface as was reported by Lyubimov.[9] The interaction of this wave-driving bulk convection flow with the surface tension force can generate two symmetric vortical flows on the free surface, which also have larger diameter (see Fig.3(b)). If the amplitude increases, the Schiliching mechanism is enhanced and part of the wave-driving flow is compressed. So the diameter of the original vortices becomes smaller. This causes more vortices to appear on the free surface (see Figs.3(c) and 3(d)).

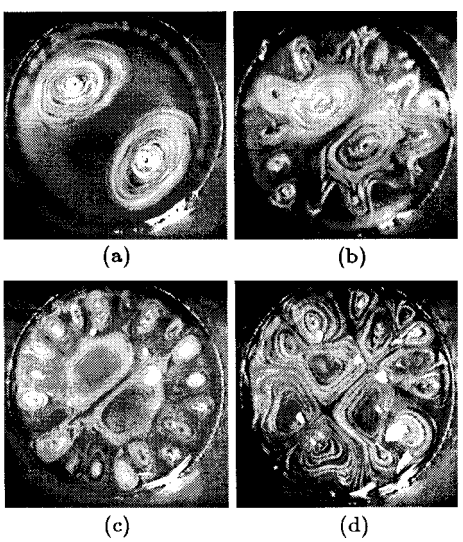


Fig.5. Another type of typical steady surface flow pattern. (η=10cp and l=5). (a) a=48.8, (b) a=53.4, (c)a=56.6, (d) a=64.4μm.

The viscosity η and the liquid aspect ratio l also have great effects on the flow patterns. Figure 5 illustrates another type of steady flow pattern with increasing amplitude. This flow usually occurs for higher η and l values. In these cases, some vortices with much smaller diameters can be seen along the rigid wall at high amplitudes. These flows are considered to be driven directly by the Schiliching mechanism. Near the centre of the surface, the original two vortices still exist. This is because a higher viscosity would lead to the effect of the Schiliching mechanism being limited only in a narrow area near the rigid walls. Figures 5(b) and 5(c) show the flows stirred by the combination of wave mechanism and Schiliching mechanism. Higher amplitudes cause the Schiliching-mechanism-driving flows to grow (see Fig.5(d)). However, with very high viscosities, there is only one type of steady flow structure appearing with increasing amplitude regardless of the variation of l, when the surface wave is highly damped by the viscous force (Fig.6).

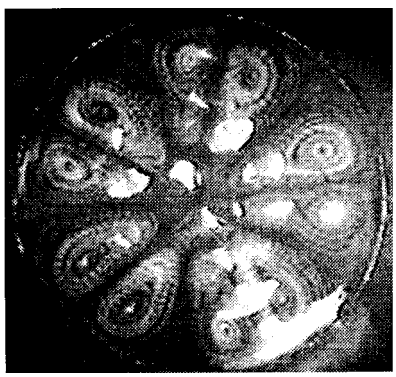


Fig.6. Steady flows with a high viscosity (η >15cp).

3.2. Effects of vibration on flow velocities

The velocity of surface flow varies greatly for different flow patterns. Figure 7 plots the variation of the surface streaming velocity with the vibration amplitude in a fixed flow pattern of two vortices. It is concluded that within the range of our investigation, the curve of velocity versus amplitude is nearly parabolic. At low amplitudes, the velocity increases slowly while at comparatively high amplitudes it increases rapidly. Furthermore, higher viscosity can reduce the flow velocity.

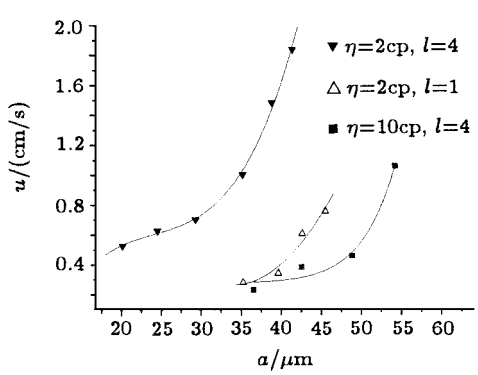


Fig.7. Variation of surface flow velocity (u) versus vibration amplitude (a) in a fixed flow structure. (The flow is composed of two symmetrical vortices).

This is in good accordance with the reports on bulk convection velocities of liquid phase in Czochralski crystal growth by Zharikov.[19] However, it differs from the surface streaming flow velocity of a liquid bridge in floating-zone techniques[14] where the velocity is proportional to the vibration amplitude.

In conventional acoustic streaming, the streaming velocity is proportional to the square of the vibration amplitude,[20] so in our experiments the surface streaming flows are likely acoustic streaming flows. It is easily understood that the velocity decreases with rising viscosity, due to the viscous resistance.

4. Conclusions

Axial vibration with high frequency and small amplitude of a cylindrical container which is filled with liquids can lead to steady surface streaming flows. When the frequency is 100Hz, amplitudes less than 100μm will agitate distinct surface flows. With the increase of amplitude from zero value, the surface will change from rest state to steady flows, and further to periodical or turbulent flows. The transition from a steady flow to an unsteady one is characterized by the value of critical Reynolds number $(Nr_e)_c$, which is $10^{-2} - 10^{-1}$. The critical values are related to the liquid physical properties as well as to the aspect ratio. At low amplitudes, the surface wave driving flow mechanism is dominant and then the steady surface flow structure is formed with two symmetrical vortices. If the amplitude is increased, the Stokes boundary layer mechanism becomes dominant and then more small vortices are generated near the rigid wall. Very high viscosity may highly damp the surface waves, and causes the surface flow formed with several vortices near the rigid wall. For a fixed steady flow structure, the velocity increases with the increasing amplitude parabolically.

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