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Vibrations

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15.1 Introduction

Vibrating a fluid corresponds to submitting it to a periodic acceleration. We describe below how, in addition to the periodic displacements that result from the vibration, mean movements can follow. Such movements can produce in space the same effects as gravity do on Earth [1] or, alternatively, compensate on Earth the gravity-induced flows as if the fluid were in space. It is this latter aspect that we emphasize in the following.

A vibration can be decomposed into its Fourier harmonic components. For the sake of simplicity, we thus only consider linearly polarized, harmonic vibration whose amplitude X varies with time t as

$$X = a \cos \omega t. \tag{15.1}$$

Here a is amplitude, $\omega = 2\pi f$ is the angular frequency, with f the frequency. When submitted to such a vibration, homogeneous matter is subjected to periodic displacements and acquires periodic velocity $u = -a\omega \sin \omega t$ and acceleration $g = -\omega^2 X$. A fluid, however, is in general not homogeneous in density because it exhibits several phases and/or is involved in mass/heat transfer processes where density gradients are the result of thermal gradients. Likewise, density gradients can be caused by concentration gradients arising from e.g. diffusive process, mixing or rejection/incorporation of solute at the solidifying interface. External accelerations thus act on density gradients and can couple with other gravity-induced flows. Local fluid velocity depends on the local density by inertial effect. It results in local velocity gradients, shear flows and Bernoulli pressure difference, especially across interfaces. Mean

displacements, convective flows and instabilities, similar to those induced by buoyancy, can thus follow. They combine with gravity-induced flows and can cancel them.

Phenomena will be different according to the relative importance of the vibration period, $1/f$, and the typical hydrodynamic times, τ (viscous relaxation, thermal diffusion, etc.). What also matters is the relative amplitude vibration with respect to the fluid container size, e. The most interesting situation is the high frequency and small amplitude limit, $\tau f \gg 1$ and $a/e \ll 1$ where local fluid inhomogeneities undergo small vibrations around their mean position while mean flow and interface ordering take place. Typically, $a = 0.1$–2 mm and $f = 1$–100 Hz.

15.2 Thermovibrational Convections

Of particular importance is the effect of vibration on a fluid submitted to a temperature gradient. The latter results in a density gradient sensitive to the vibration. Let us thus consider a fluid submitted to a vibrational acceleration in a thermal gradient in the Rayleigh–Bénard configuration (two parallel plates with a temperature difference ΔT separated by distance e). According to Gershuni and Lubimov [2], vibrational Rayleigh number (ρ is density, p is pressure, T is temperature, D_T is thermal diffusivity) is written as:

$$\mathrm{Rav} = \frac{\left[a\omega \left(\frac{\partial \rho}{\partial T} \right)_p \Delta T e \right]^2}{2\pi D_T}. \tag{15.2}$$

The convection threshold depends on the angle between the thermal gradient and the vibration direction. There is no convection for a temperature gradient parallel to the vibration. The most unstable situation corresponds to a temperature gradient perpendicular to the vibration direction. Here, convection starts when Rav is larger than a few thousands.

15.3 Crystal Growth

These thermovibrational flows can annihilate thermogravitational flow such as buoyancy and/or thermocapillary (Marangoni) convection when an interface is present, depending on the mutual orientation of vibration axis and thermal or compositional gradient. In the system with free interface thermo-(soluto-) capillary (Marangoni) and thermovibrational mechanisms can

produce motion in opposite directions. This is particularly the case in a solidification process. Appropriate combination of these mechanisms can then be used to counteract the usual convective flows inherent in crystal growth processes from the liquid phase.

Efficient control of heat and mass transfer during real industrial applications of crystal growth from the liquid phase can be envisaged. The possible utilization of such a strategy for the floating zone crystal growth technique has been addressed [3, 4].

15.4 Dynamic Interface Equilibrium

Harmonic vibrations can considerably deviate the equilibrium position of an interface from its normally horizontal position under gravity acceleration, g, and attain large enough angles [5]. The situation is similar with that of simple mechanical systems under vibration. For example, a simple pendulum of length L can be stabilized in an upside down position by vertically vibrating its support at a frequency much larger than the natural frequency of the pendulum, that is, when $a\omega \geq \sqrt{2gL}$ [6]. When the support of the pendulum is vibrated horizontally at frequencies much larger than the natural frequency of the pendulum and vibrational velocity amplitudes $a\omega$ higher than a threshold value ($a\omega \geq \sqrt{2gL}$), the equilibrium position of the pendulum is no more vertical and makes an angle with respect to the horizontal.

Vibration of a fluid interface can demonstrate similar phenomena. Using vibration, it is possible to stabilize two-fluid configurations, generally unstable when the vibration is absent. For example, a heavier fluid floating over a lighter fluid under terrestrial gravity field is unstable (Rayleigh–Taylor configuration) under normal conditions. Application of strong vertical vibration can dynamically stabilize the above configuration [5]. When subjected to strong horizontal vibration, the interface of an initially horizontal fluid interface can attain a dynamic equilibrium at an angle to the horizontal plane.

Beyond a threshold value of vibrational velocity $a\omega$, the interface attains an equilibrium position at an angle α with vertical (Figure 15.1). The results depend on gravity acceleration g, vibration amplitude and frequency [5]. With L the dimension of the interface the angle can be written as

$$\sin \alpha = \frac{2gL}{\pi a^2 \omega^2} \frac{\rho_\ell + \rho_v}{\rho_\ell - \rho_v} \tag{15.3}$$

When the density difference between phases is small, the interface can exhibit instability of Kelvin–Helmholtz type called "frozenwave" [7]. It is
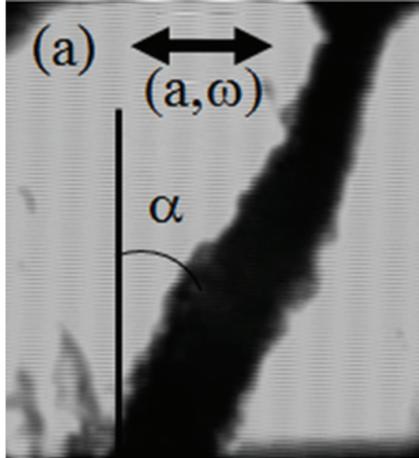
Figure 15.1 Interface position in liquid–vapor hydrogen for the vibration case $a = 0.83$ mm and $f = 35$ Hz and gravity level $0.05g$ (directed vertically). The interface looks fuzzy as it pulsates at the vibration frequency.
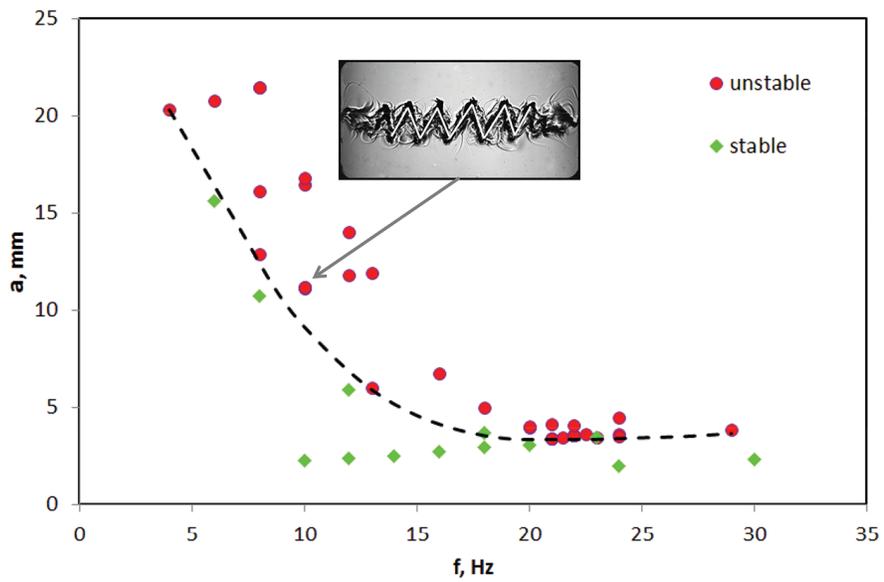

Figure 15.2 Experimental stability map in the plane (a, f) for miscible liquid/liquid interface (mixtures of water–isopropanol of different concentrations). Diamonds: no instability. Circles: instability. The black dashed curve is a guideline for eyes between stable and unstable regions. Inset: Typical shape of the frozen waves with horizontal vibration.

characterized by an interface modulation perpendicular to vibration direction that keeps immobile in the sample reference frame. This instability is also present when two miscible liquids of similar (but nonidentical) viscosities and densities are present [8]. While it was shown experimentally that surface tension can be nonzero between miscible liquids [9], its value is, however, quite small. From the experimental results [8], the values of the critical amplitude were determined as a function of critical frequency as shown in Figure 15.2. In this phenomenon, gravity is in competition with vibrational effect as surface tension does not play a role.

References

[1] Beysens, D. "Critical Point in Space: A Quest for Universality." *Microgravity Science and Technology* 26 (2015): 201–218.

[2] Gershuni, G.Z., and D.V. Lyubimov. *Thermal Vibrational Convection*, New York, NY: Wiley, 1998.

[3] Lyubimov, D.V., T.P. Lyubimova, S. Meradji, and B. Roux. "Vibrational Control of Crystal Growth from Liquid Phase." *Journal of Crystal Growth* 180 (1997): 648–659.

[4] Lappa, M. "Review: Possible Strategies for the Control and Stabilization of Marangoni Flow in Laterally Heated Floating Zones." *Fluid Dynamics & Materials Processing (FDMP)* 1, no. 2 (2005): 171.

[5] Landau, L.D., and E. M. Lifschitz. *Mechanics*. Moscow: Mir, 1973.

[6] Gandikota, G., D. Chatain, T. Lyubimova, and D. Beysens. "Dynamic Equilibrium Under Vibrations of H_2 Liquid-Vapor Interface at Various g-levels." *Physical Review E* 89 (2014): 063003–7.

[7] Gandikota, G., D. Chatain, S. Amiroudine, T. Lyubimova, and D. Beysens. "Frozen Wave Instability in Near Critical Hydrogen Subjected to Horizontal Vibration Under Various Gravity Fields." *Physical Review E* 89 (2014): 012309–1.

[8] Gaponenko, Y.A., M. Torregrosa, V. Yasnou, A. Mialdun, and V. Shevtsova. "Dynamics of the Interface Between Miscible Liquids Subjected to Horizontal Vibrations." *Journal of Fluid Mechanics* (accepted, 2015).

[9] Lacaze, L., P. Guenoun, D. Beysens, M. Delsanti, P. Petitjeans, and P. Kurowski. "Transient Surface Tension in Miscible Liquids." *Physical Review E* 82 (2010): 041606.