VIBRATING LIQUIDS IN SPACE

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Natural convection is generated by buoyancy or capillary forces, but other forms of flows are possible when fluids are exposed to external vibration. Is it possible to mix liquids by shaking a completely filled container? An experiment is looking for answers on board the International Space Station

Everybody is familiar with the action of gravity on a fluid where density gradients are present due to heating or compositional difference. Due to buoyancy, the denser portions sink to the bottom of the container, pushing away the lighter ones. As a result, convection sets in, transporting heat and mass. In weightlessness conditions, this driving force is absent but inertia exists as the tendency of a body to resist acceleration. When a container filled with liquid is subjected to high frequency vibrations, the fluid is not able to react due to inertia and this may create a flow. If the density is uniform, then the fluid moves as a solid body. However, when density gradient is present, also inertia will not be uniform, resulting in convective motion. Obviously, there is analogy between gravity-induced and inertia-driven convection, as a result of the Einstein equivalence principle, although the second one is almost unknown. What would be the impact of vibration on dispersion by molecular diffusion and heat transfer without buoyancy?

Vibration-induced convection

More than 30 years ago, Gershuni and Zhukhovitskii predicted that the application of controlled, high-frequency vibrations to a fluid system with macroscopic density gradients would give rise to flows across the sample [1]. Density gradients can be generated in a single-component fluid when a temperature difference is established across the container or in a fluid mixture where the concentration of different species is not homogeneous. Depending on the case to be studied, the effect is known as thermovibrational and solutovibrational convection, respectively. Naturally, the behaviour of a fluid system depends on the properties of the external vibrations. Here we restrict the discussion to a binary mixture subjected to *high* frequency vibrations. This applies to vibrations with a period similar to or smaller than the viscous (L^2/ν), thermal (L^2/χ) and mass diffusion (L^2/D) time, where L is a characteristic length of the container, ν the kinematic viscosity, χ the thermal diffusivity and D the

▲ The International Space Station as seen from the space shuttle Endeavour during the return flight of the STS-130 mission (February 2010) that brought to ground the hard disks with images and data from the IVIDIL experiment (credits: NASA).

mass diffusion coefficient. Under these rather general conditions, a mean flow with “slow” characteristic timescales develops, superimposed on a fast oscillating contribution that has the same frequency as the imposed external vibration. The difference between slow and fast oscillations is shown in Fig. 1, where simulated trajectories of a few particles are traced during the same time interval. Large diagonal and two corner rolls demonstrate the slow motion (“streaming”) while high-frequency and small-amplitude oscillations correspond to “fast” motion. Vibration-induced mean flows have been extensively studied theoretically in single liquids and binary mixtures [2-4] (a comprehensive review is given in [2]). As in other forms of convective instabilities, the strength of vibration-induced convection is characterized by a hydrodynamic number. For the low vibrations that is the vibrational analogue of the Rayleigh number for buoyant convection, where the gravity is replaced by a vibration acceleration proportional to $A\omega^2$, A and ω being the amplitude and frequency of vibration, respectively. However, for the case of interest, *i.e.*, high-frequency vibrations, the analogue dimensionless number has a more sophisticated origin and follows an averaging approach [1-6]. It was suggested that it should be called the Gershuni number [5-7] to mark his significant contribution to the theory of thermovibrational convection, $Gs = (A\omega\beta_T\Delta TL)^2/2\nu\chi$ (β_T , ΔT , L , ν , χ being the thermal expansion coefficient, temperature difference, sample thickness, kinematic viscosity and thermal diffusivity, respectively).

Notwithstanding the fact that vibrational convection is fairly well understood in numerical and theoretical studies, no experimental evidence has been made available until

▼ FIG. 1: Fast and slow motion generated by vibrations. Trajectories of different fluid particles are shown by different colours. The small amplitude oscillations (fast) correspond to external frequency and the big roll is “slow” convective motion.

▲ FIG. 2: ESA astronaut Frank DeWinne, working with the IVIDL experiment on the ISS.

very recently [5,6] due to the fact that buoyancy-induced flows are usually dominant over vibration-induced ones, therefore preventing their observation. As such, vibrational convection would become detectable in a reduced gravity environment, where buoyancy forces are “switched off” and the only forces acting on the fluid are the ones induced by the external forcing.

The IVIDL experiment

The study of vibration-induced convection is not just a purely academic problem for the advancement of our understating of hydrodynamic instabilities. There is a unique environment where this phenomenon may have tangible effects: the Columbus laboratory on board the International Space Station. There, slowly but steadily, experiments in fluid physics and material science are being performed since its activation in 2008. A few of them are dedicated to the measurement of (thermal)diffusion coefficients of multi-component liquid mixtures and metallic melts that are impossible to determine with a comparable precision in a normal gravity environment. In order to obtain an accurate measurement, macroscopic flows must be absent from the sample volume to avoid distorting the diffusive fronts. But while buoyancy is negligible, external vibrations, or g-jitter, are always present and may give rise to convective currents therefore affecting the measurements.

This is the main motivation behind IVIDL (Influence of Vibration in Diffusion in Liquids), a project proposed to the European Space Agency (ESA) in 2000 by an international team including the Microgravity Research Centre of ULB (Brussels, Belgium), the Institute of Continuous Media Mechanics UB RAS (Perm, Russia) and Ryerson University (Toronto, Canada) and coordinated by the Brussels team. The project proposes to study the influence of vibrations on the measurement of diffusion and Soret (or thermal diffusion) coefficients in well known two-component mixtures by monitoring the temperature and concentration fields during diffusion.

▲ FIG. 3: 3D “tomography” of concentration field and its cross-section in two perpendicular directions at the central part in case of no (a), and weak ($Gs = 800$) vibration (b). 3D surfaces of iso-concentration are shown by different colours.

After several years of preparatory activities, the project culminated in 2009 with the performance of a three months experiment on board the ISS.

During each experimental run, a temperature difference is established across the cell, to achieve a separation of components as induced by the Soret (or thermal diffusion) effect. Then, the temperature difference is switched off, the cell is brought rapidly to isothermal conditions and the components get back to a homogeneous distribution. While the process takes place, the sample is shaken perpendicularly to the temperature gradient, with frequencies up to 2.8 Hz and amplitudes up to 68 mm. Part of the images acquired in the many runs performed were transmitted to ground and monitored by the different teams involved.

A sophisticated post-processing of interferograms allowed the quantitative observation of (thermal)diffusion processes as well as transient and steady state vibrational convection. Preliminary analysis has provided valuable insights into the formation and evolution of the concentration field with and without the action of vibrations. The central parts in plots of Fig. 3 show 3D surfaces of iso-concentration after 12h from the beginning of the experiment. Side graphs show central cross-sections of concentration field in two perpendicular directions (not near the walls). In the absence of external vibration the concentration field follows the structure of the temperature field (Fig. 3a). As experiments

are never “ideal”, the temperature field in IVIDIL is not perfectly linear approaching the corner regions, even though this “non-ideality” does not provoke convection in weightlessness. Hence, there is no motion in the system and 3D iso-surfaces are almost parallel, their shape resembling the roof of a “pagoda”.

The situation is very different in the presence of vibrations: iso-surfaces are twisted by the flow as shown in Fig. 3b. The concentration field in the direction perpendicular to vibrations (graph of projections on the right side) gives an idea about the flow structure: four vortices are formed somewhat similar to those shown in Fig. 1 and is similar to a convective roll as observed in thermal convection. The increase of the vibrational energy, *i.e.* Gershuni number, will lead to more sophisticated flow patterns.

The 3D pictures in Fig. 3 were created on the basis of raw interferogram images obtained on the ISS that are shown in Fig. 4a. Besides the qualitative data, the accuracy of the experiment has also allowed quantitative data to be obtained, which are presented in Fig. 4b. Experimental data have been compared with numerical predictions, where concentration profiles along the temperature gradient in the middle of the cell (along central vertical line in 3D pictures in Fig.3) are presented.

The concentration profile in the absence of vibration (Fig. 4b) is linear and in excellent agreement with numerical predictions. This suggests that g-jitter did not affect diffusion at the present level of accuracy. However, high-frequency imposed vibrations do affect the mass transfer. The concentration profiles in the case of relatively weak forcing ($f=2\text{Hz}$, $A=44\text{mm}$, $Gs=800$) deviate from the linear profile due to the flow as shown in Fig. 4b on the right plot.

While the analysis of the full set of data received from space is ongoing, it is believed that IVIDIL will shed light on the complex mechanisms behind vibration-induced convection, and will provide useful insight on how to control fluids in space to support future physical and life science experiments. ■

▼ FIG. 4: (a) Typical interferograms of two perpendicular views of the cell. (b) Experimental (pink) and numerical (black) concentration profiles in the middle of the cell for water (90%) - isopropanol (10%) mixture with negative Soret coefficient ($t=12\text{h}$).

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