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STUDY OF FLUID BEHAVIOUR UNDER GRAVITY COMPENSATED BY A MAGNETIC FIELD

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Fluids, and especially cryogenic fluids like Hydrogen H_2 and Oxygen O_2, are widely used in space technology for propulsion and cooling. The knowledge of fluid behaviour during the acceleration variation and under reduced gravity is necessary for an efficient management of fluids in space. Such a management also asks fundamental questions about thermo-hydrodynamics and phase change once buoyancy forces are cancelled.

For security reasons, it is nearly impossible to use the classical microgravity means to experiment with such cryofluids. However, it is possible to counterbalance gravity by using the paramagnetic (O_2) or diamagnetic (H_2) properties of fluids. By applying a magnetic field gradient on these materials, a volumic force is created that is able to impose to the fluid a varying effective gravity, including microgravity.

We have set up a magnetic levitation facility for H_2 in which many experiments have been performed. A new facility for O_2 is under construction that will enable fast change in the effective gravity by quenching down the magnetic field. The facilities and some particularly representative experimental results are presented.

I. The principle of magnetic levitation

When a fluid is subjected to a magnetic field it becomes magnetized, i.e. it itself becomes a magnet. If, in addition, the magnetic field varies in space, the fluid experiences a force per unit volume $\vec{F}$ which is given by the following expression

$$\vec{F} = \frac{\chi}{\mu_0}\left(\vec{B}\cdot gr\vec{a}d\right)\vec{B}$$

where χ is the magnetic susceptibility of the fluid, μ_0 the permeability of vacuum, $\vec{B}$ the magnetic flux density, and $gr\vec{a}d$ the gradient operator.

This force can be used to compensate gravity. However, the magnetic field amplitude required for levitation is generally very large. For example, to levitate hydrogen in a solenoid coil of 90 mm inner diameter and 200 mm height, a central field of 10 Tesla is necessary. In order to attain these values a superconducting coil is needed.

Yet, this method has its limitations: a magnetic force can perfectly compensate the earth gravity only on one point of the sample. By using the Maxwell equations for $\vec{B}$, it can be shown that the vector expression $\left(\vec{B}\cdot grad\right)\vec{B}$ representing the force can only be either a space-varying function or zero [1, 2]. Therefore, away from the point of perfect compensation, residual forces appear so the studies have thus to be carried out in small experimental cells in order to ensure a good compensation in the entire volume. For example, to ensure residual forces less than 1.5% of the earth gravity, a 3mm x 3mm sample had to be used (following section).

II. Our magnetic levitation facility for hydrogen

The magnetic levitation facility for hydrogen at CEA-Grenoble is based on a 10 Tesla superconducting magnet coil with a useful inner diameter of 90 mm diameter, and has been operational since 1995. Many experiments have been performed in this facility in collaboration with other French teams from CNRS, CNES and University of Marseille. As shown in Fig.1, the facility is composed of a cryostat that houses the niobium titanium superconducting coil immersed in liquid helium at 2K and a central vacuum can containing the experimental hydrogen condensation cell. Different kinds of cell can be used depending on the experiment requirement. The cell presented here is entirely made from sapphire. The cell volume is cylindrical, 3 mm in diameter and 3 mm in length. It is placed at a well defined position of the vertical solenoid axis where the levitation force is at its maximum. The temperature of the cell is controlled to within 1mK. The experiment can be observed by means of a cryogenic endoscope that brings the image of the cell to a CCD camera placed on top of the cryostat.

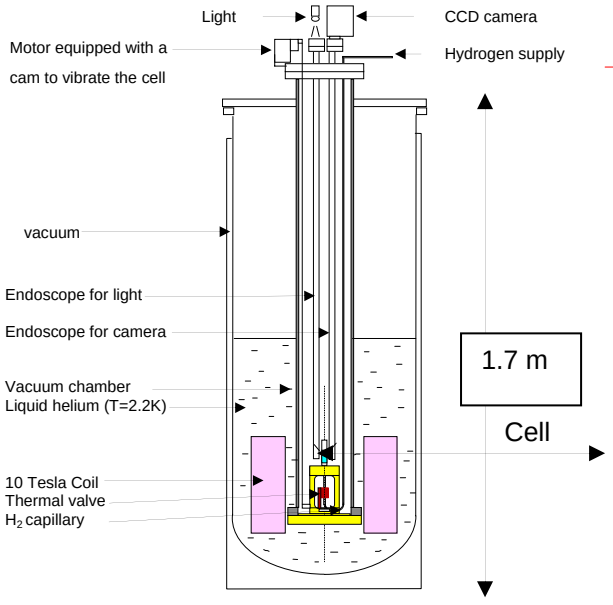

Fig 1-a : Schematic of the cryostat.

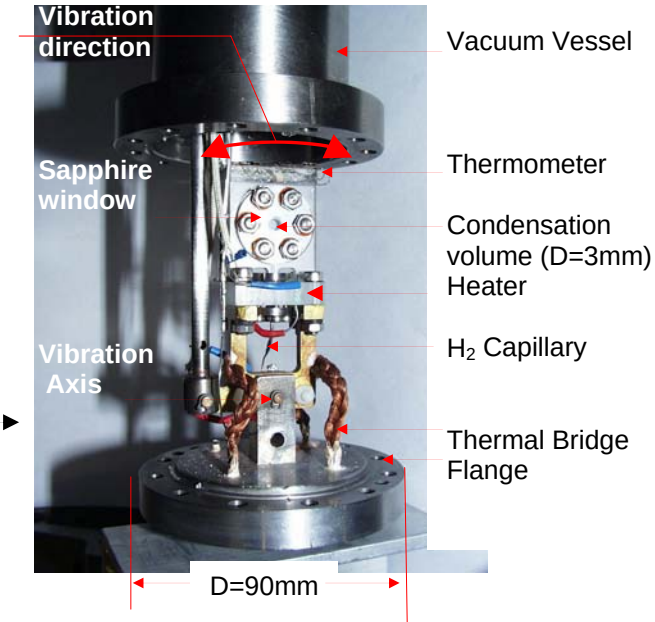

Fig 1-b : Picture of a cell that can be vibrated at up to 50 Hz with 0.5 mm amplitude.

The pictures in Fig.2 show a stratified liquid/vapour mixture of hydrogen contained in the cell described above under gravity (Fig.2 left) and under magnetic compensation of gravity (Fig.2 right).

In our magnet facility, we were able to reproduce the general features of experiments that have previously been performed in the Space Shuttle, the MIR station and in sounding rockets. An example is described in the next chapter. Two more experiments are presented in Refs. [3, 4].

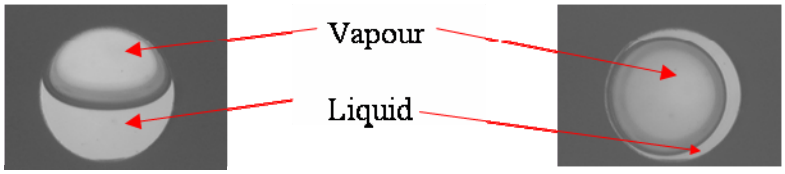

Figure 2 : The experimental cell filled with a liquid/vapour mixture of hydrogen viewed along its horizontal axis. Left: The magnetic field is zero. The liquid is at the bottom of the cell and the vapour is above; the curved interface is a result of capillary forces. Right: The magnetic forces compensate gravity. The liquid wets the walls and the vapour bubble is perfectly circular (as if it were in space).

III. The phase transition of hydrogen near its critical point

The critical point of a fluid is the point in the phase diagram beyond which any distinction between the liquid state and the vapour state disappears. We are in the presence of a single-phase fluid. For hydrogen, the critical point is at 33 K and 13 bars. At this point the specific heat and the thermal conductivity become very large while the superficial tension and the thermal diffusivity go to zero.

What happens when crossing the critical point?

As shown in Fig.3, when a closed cell half-filled with liquid is heated, the pressure rises with increasing temperature following the coexistence curve of gas and liquid. As we go closer to the critical point it is harder to distinguish the liquid/vapour interface (Fig.3a - Fig.3c). If the critical point is crossed, the interface disappears completely (Fig.3d). If the cycle is inverted, that is, the critical point is crossed by cooling the cell, phase transition occurs, a fog of droplets, opaque to light, is produced (Fig.3e). The fluid then reorganizes itself, i.e. the liquid falls to the bottom and the vapour moves to the top (Fig.3e - Fig.3h). Under gravity, the time needed to reorganize the two phases is very short (a few seconds) because gravity helps droplet coalescence by buoyancy.

If the experiment described above is carried out under gravity compensation, we see something quite different. Figure 3i shows the hydrogen cell for $T = T_c - 1$ K. As temperature is increased, the liquid/vapour interface disappears (Fig.3j - Fig.3l). The cell is then cooled to 5 mK below the critical temperature (Fig.3m - Fig.3o). Just as in the experiment under gravity a fog of droplets appears. However, this time, the turbidity due to the “fog” stays for a number

of minutes. Without gravity effects, buoyancy is suppressed and the droplet coalescence is greatly slowed down; a longer time is needed to reach the equilibrium state of Fig.3i.

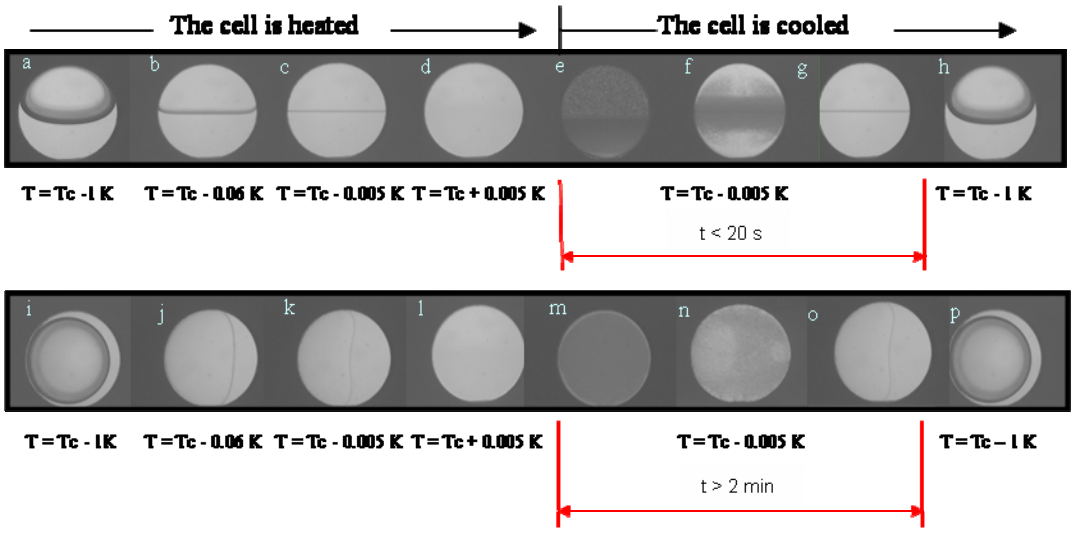

Figure 3 : Snapshots showing the fluid crossing its critical point under earth gravity (a-h) and under microgravity (i-p).

Under microgravity, the late stages of phase transition in gas-liquid systems is driven by droplet coalescence only and obeys two universal scaling laws of growth [5]. The key parameter is the volume fraction ϕ of the minority phase ($\phi = V_g/(V_g+V_l)$, with $V_{g,l}$ the volume of gas (g) and liquid (l)).

If $\phi < 0.3$, growth is driven by droplet coalescence controlled by Brownian motion -induced collisions. The typical evolution law of the droplet size L_m varies as $t^{1/3}$ where t is time. If $\phi > 0.3$, the flow resulting from droplet coalescence is able to induce additional coalescence in a chain reaction that eventually leads to an interconnected pattern. In this case it has been found that L_m follows a linear growth law given by $L_m = b\,U\,t$, where $U = \sigma/\eta$ is growth velocity; η is the (shear) viscosity, σ is the gas-liquid interfacial tension and $b \cong 0.03$ is a universal constant, independent of fluid properties.

…and when vibrations are superimposed?

We have recently performed some experiments to determine the effect of vibrations on the droplet coalescence kinetics [5]. In our facility, a device enables the experimental cell to be vibrated in a horizontal direction that is perpendicular to the cell axis. The oscillatory motion is sinusoidal with frequencies up to 50 Hz and an amplitude of up to 0.5 mm. Figure 4 shows the results of an experiment with $\phi = 0.5$. At early times the pattern exhibits a linear growth (part (a) of the curve) which does not appear to be affected by vibration. However, when the droplet size L_m exceeds a given size L_o, an increase in the slope of the growth law is observed (part (b) of the curve).

The key parameter in the transmission of the vibration to the gas and liquid phases is the thickness δ of the viscous boundary layer

$$\delta = \left(\frac{2\eta}{\rho\omega} \right)^{0.5}$$

where η and ρ are the viscosity and density of the fluid, and ω the vibration circular frequency. When $L_m << \delta$, the two phases strongly interact by viscous shear and move coherently. The growth is thus unaffected by vibrations. However, as soon as $L_m > \delta$, the motions of the two phases are locally decoupled. Due to inertial effects, the gas and liquid phases no longer move at the same velocity. The associated shear flow and the Bernoulli pressure at the interface stretch the domains and deform the gas-liquid interface, resulting in an increase of the growth velocity U. The length L_o that separates the two growth regimes then corresponds to the thickness of the viscous boundary layer, $L_o \approx \delta$.

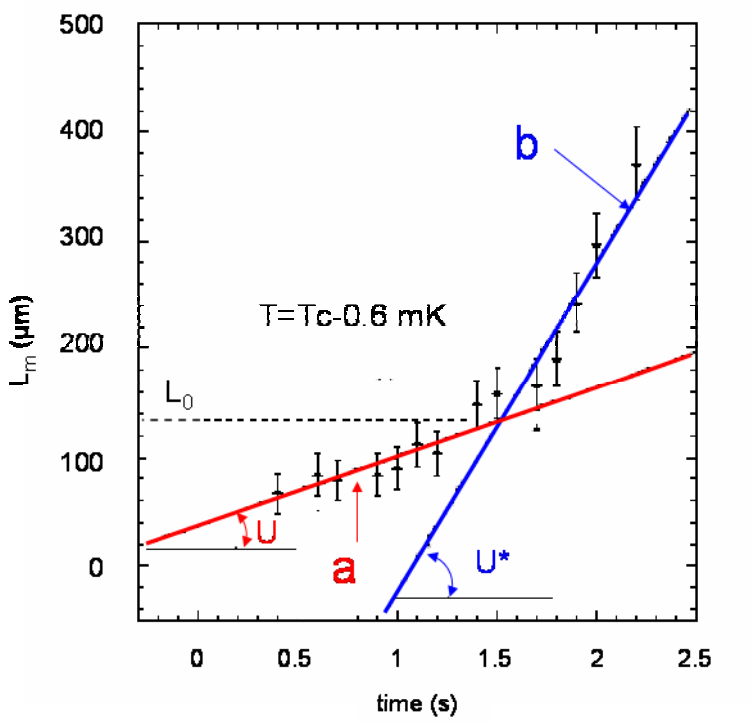

Figure 4: Typical evolution of the hydrogen droplet size L_m during condensation under microgravity and harmonic vibrations (frequency 20.3 Hz, amplitude 0.3 mm). Only part b of the curve is affected by vibrations. The growth velocities U and U^* are functions of T_c - T. The cross-over length L_0 = 140 µm in the present experiment is in the same order of magnitude as the calculated value for the viscous boundary layer δ.

IV. Conclusion and future plans

Magnetic levitation is a way to perform experiments usually carried out in space or in sounding rockets at a much lower cost and/or with fluids (hydrogen, oxygen) that cannot be loaded for safety reasons. Small samples, in the order of a few cm^3, have to be used to make the unavoidable residual forces negligible. The use of magnetic forces appears to be a very powerful tool that allows samples to be placed not only under compensation of gravity but also under a time dependent gravity. In support of this claim, two typical experiments performed with hydrogen have been presented.

A new facility dedicated to O_2 is presently under construction in our laboratory. Oxygen exhibits a much larger (para) magnetic susceptibility than hydrogen. Oxygen will be studied not only under zero gravity, but also under rapid change of gravity by tuning the magnetic field, thus reproducing the ballistic phases of a spacecraft. This new facility, called OLGA (for Oxygen Low Gravity Apparatus), makes use of a 300 mm inner diameter superconducting coil with a maximum field strength of 8 Tesla. The main advantage of OLGA over the liquid hydrogen facility described above is the large inner diameter of the magnet coil. It allows the use of much larger sample volumes under a given restriction on residual forces: here 10 cm^3, compared to 0.1 cm^3 in the existing facility. The first experiment planned in OLGA is the study of the burnout in liquid oxygen under reduced gravity in collaboration with Air Liquide Company and CNES. The facility should be operational by the end of 2005.

Acknowledgments

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