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Magnetic compensation of gravity: experiments with oxygen

The CEA Grenoble, through the ESEME/SBT team, has developed a new ground based facility providing magnetic compensation of gravity in oxygen. A 2T superconducting magnetic coil has been used to create the magnetic field. The installation is described. Well adapted to the heat and mass transfer studies, for example of the various boiling regimes, it permits to enhance the understanding of these phenomena in reduced gravity and gives a convenient way to reproduce space conditions on the ground. The first experimental results are presented.

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1. Introduction

Reigniting cryogenic engines in space is a challenge that the SNECMA Company, builder of the Ariane V rocket engine, tries to solve. Phenomena occurring in microgravity are still to be understood, such as cryogenic engine cooling before ignition, fuel behaviour in tanks, etc. A new facility OLGA (Oxygen Low Gravity Apparatus) has been developed at CEA/Grenoble. OLGA provides the magnetic compensation of gravity in liquid oxygen in a few cubic centimetre volume. OLGA followed the concept of the previous gravity magnetic compensation in liquid hydrogen [1, 2].

Scope of the study
OLGA is dedicated to the fundamental and applied research, such as studying phase changes, boiling, boiling crisis or fluid behaviour near the critical point. It is also involved into research and development of space engines, in particular into the study of heat and mass transfer in cryogenic engines, such as fuel behaviour in cryogenic tanks or engine precooling before reignition in space.
There are several ways of obtaining the reduced gravity (free fall tower, zero-G plane, sounding rockets, International Space Station), with penalizing drawbacks (time of microgravity or cost). Magnetic compensation using superconducting materials can theoretically give an infinite time for experiments.

Principle of magnetic compensation
In the influence area of a magnetic field, paramagnetic (e.g. oxygen) and diamagnetic (e.g. hydrogen) materials are subjected to a volume force:

$$\overrightarrow{F_{magnetic}} = \frac{\chi}{2\mu_0}\overrightarrow{grad}\left(B^2\right)$$

where χ is the magnetic susceptibility of the considered material, μ_0 is the vacuum magnetic permeability and B is the applied magnetic field. In order to compensate gravity in oxygen, the value of grad(B^2) needs to be 8.15 T^2/m at 90K.
This force, is proportional to density just like the weight [1, 2], thus the compensation of gravity occurs independently of the state of matter (liquid gas or solid).

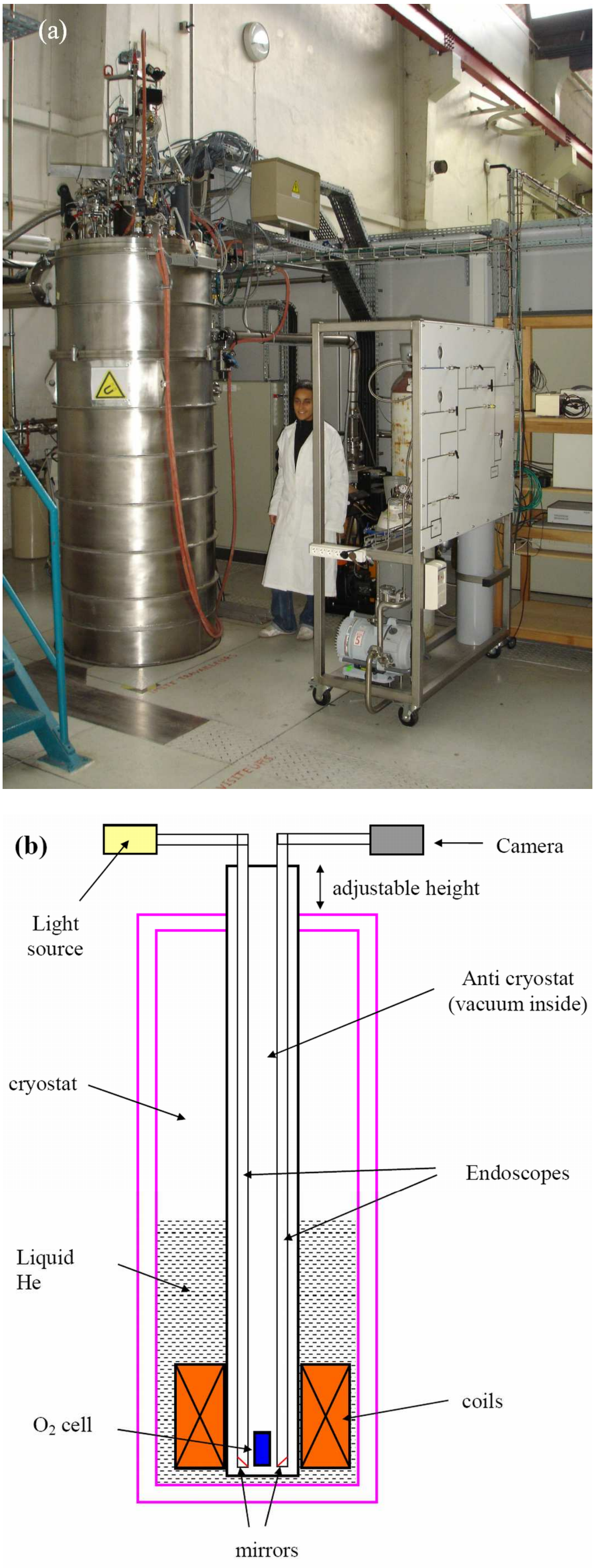

Fig. 1: General view of OLGA. (a) photo (b) schematic.

The advantages of such a technology are: microgravity time potentially infinite, adjustable gravity level and use of dangerous substances (oxygen, hydrogen).
The main drawback stays in the fact that the residual gravity field is not perfectly homogeneous.

2. Presentation of the facility

OLGA is a cryogenic facility (Fig 1). The cryostat contains two coaxial cylindrical coils made of Nb-Ti superconductor alloy (Fig 2), cooled with liquid helium at 4.2K. Their height is 555mm. The inner and outer diameters are 336mm and 650mm. Supplied with a stable current intensity up to 300A, the coils provide oxygen levitation using a current intensity of 235A, giving a B^2 gradient of 8.15 T^2/m and a maximum magnetic field of 1.5T.

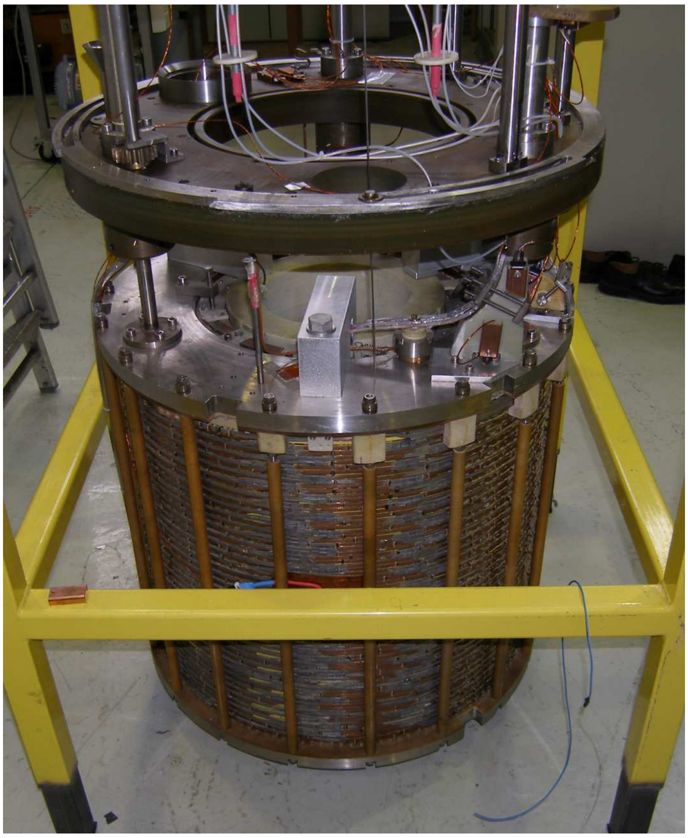

Fig. 2: Superconducting coils of OLGA.

An anti-cryostat is placed inside the cryostat through the coils. It contains the experimental cell and a visualisation system. Thanks to two endoscopes and corresponding mirrors (for light source and camera), magnetic and temperature effects on the visualisation device are avoided. The anti-cryostat is mobile and its vertical position with respect to the cryostat and the coils which are both fixed is adjustable. Both endoscopes are mobile with respect to the anti-cryostat and can move independently. Their mirrors can rotate to adjust the view angle.

Magnetic compensation limitations
It has been shown [4] that it is not possible to exactly compensate the gravity in a finite volume. It can be compensated in only one point in the present installation. A residual "gravity" field is not uniform and grows with the

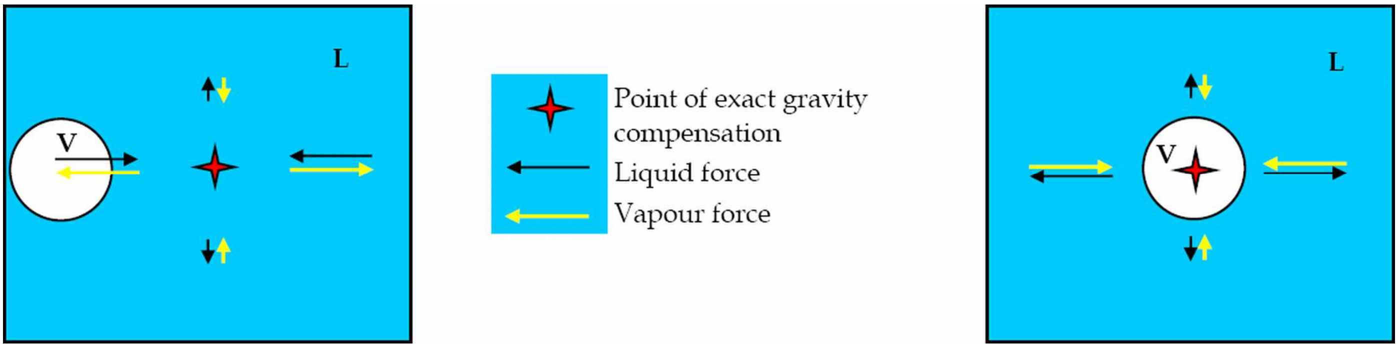

Fig. 3: Stability of the bubble position. Left: the case of a diamagnetic material, characterized by a positive magnetic susceptibility (e.g. hydrogen). Right: the case of a paramagnetic material, characterized by a negative magnetic susceptibility (e.g. oxygen). Direction and magnitude of the residual magnetic forces are shown for vapour and liquid phases.

distance from this point. The radial component of this force is the main limiting factor. The experimental cell volume is thus limited by the compensation accuracy.

This residual force influences the liquid/vapour configuration stability. For example, the stability of the position of a vapour bubble in equilibrium with the surrounding liquid depends on the type of material used. For the oxygen (paramagnetic), the residual radial force tends to gather the vapour at the point of exact gravity compensation, and reject the liquid towards the walls. As a consequence, the bubble equilibrium is stable. For the hydrogen (diamagnetic), the inverse phenomenon is observed: the vapour bubble cannot stay at the point of the exact gravity compensation (Fig. 3).

It is possible to improve the field homogeneity by adding a ferromagnetic insert [3, 4]. In our case, the insert increases the compensation volume by factor 4.5.

3. Experiments

The experiments are performed in a cylindrical cell (Fig. 4). Its dimensions are chosen to give the residual gravity level of $0.04g_0$. This leads to a 24cm^3 volume for the experimental cell.

The sapphire cylinder (30 mm diameter and 50 mm long) is closed by two copper flanges. The bottom flange contains a heat exchanger that serves to regulate the temperature. A heater placed in the bottom centre can input a heat flux up to 38 W/cm^2 during boiling experiments. Several thermistors placed in the flanges of the cell measure the local temperature. The sapphire transparency allows for the transmission observations.

4. Results of the nucleate boiling experiments

The heat flux was 1W/cm^2, applied from the bottom centre of the cell. Magnetic compensation was put on to vary residual gravity from normal gravity ($1g_0$) to $0.04g_0$. Movie recordings (Fig. 5) were made at a frame rate of 500fps. Experiments were very reproducible. The bubble behaviour could be studied, in particular bubble size and growth time.

We found that the bubble departure size r behaved similarly to the capillary length under all gravity levels (Fig. 6). Here the capillary length is defined as

$$l_c = \sqrt{\sigma/(g\Delta\rho)}$$

where σ is the interface tension, g the residual gravity, $\Delta\rho$ the difference between the density of the liquid and the vapor phases. The effective gravity level is shown in the graph too.

Another result concerns the departure period t_{res} (the duration between successive bubble departures). It has been found to be proportional to the thermal growth time T_{thg} (Fig. 7), which is defined as

$$T_{thg} \propto D_l \left(l_c \rho_v \frac{H}{\lambda_l \Delta T} \right)^2$$

where D_l is the liquid thermal diffusivity, ρ_v is the density of the vapour phase, H is the evaporation latent heat, λ_l is the

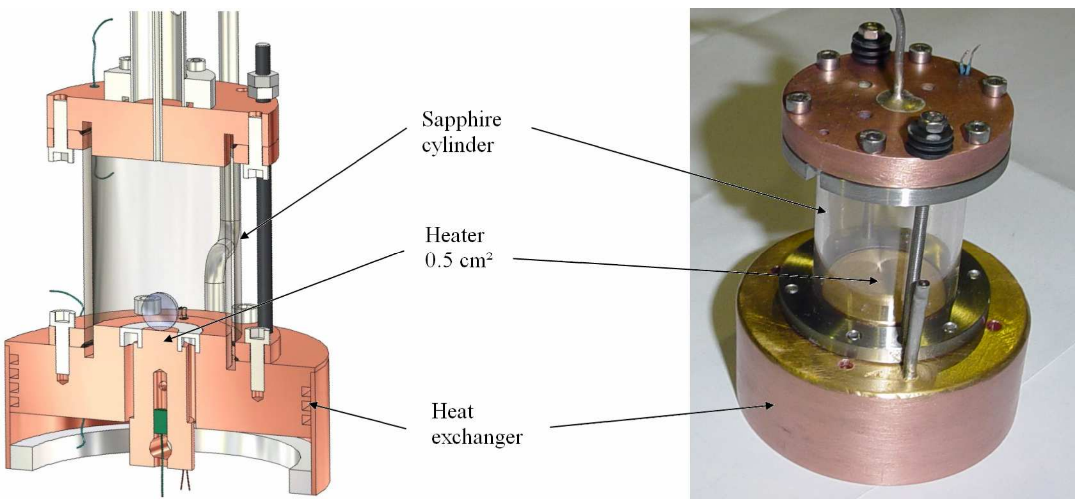

Fig. 4: Test cell used for studies of boiling heat transfer at low pressure

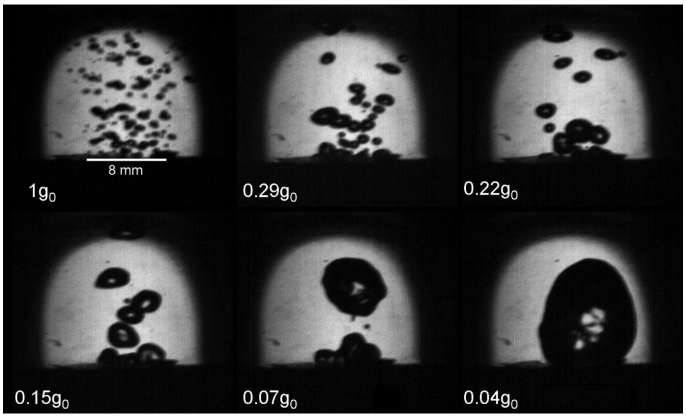

Fig. 5: Nucleate boiling under variable gravity. The values below the pictures give the level of residual gravity.

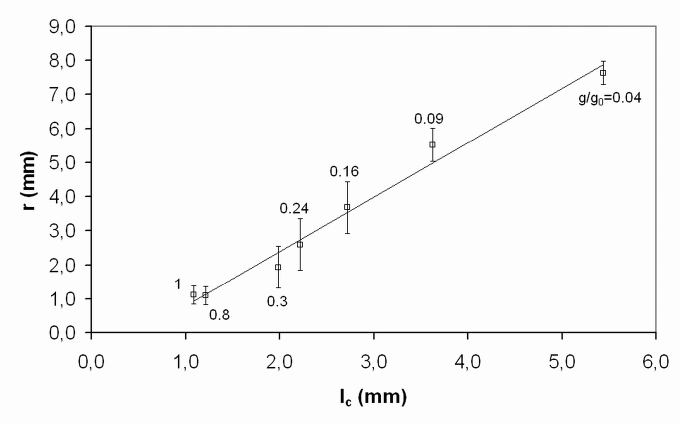

Fig. 6: Bubble radius at departure versus capillary length. The gravity level for each point is shown.

liquid thermal conductivity, and ΔT is the difference between the heated surface temperature and the saturation temperature [5].

These results are similar to those of Qiu and Dhir [6] obtained with saturated water under 1 bar in parabolic flights. They observed that the departing bubble radius was proportional to $g^{-1/2} \propto l_c$.

4. Conclusion and perspective

OLGA, thanks to magnetic compensation, is now operational to perform thermal transfer experiments for the effective gravity level ranging from ground conditions to space conditions. As a consequence, OLGA gives the unique opportunity to study physical phenomena under variable gravity.

Nucleate boiling experiments have been performed under variable gravity, from normal to zero gravity. Vapour bubbles behaviour was conventional for the microgravity: bubbles got larger and stayed longer on the heating surface as g decreased.

As a future improvement, a second heat exchanger with regulated temperature will be placed on the top of the cell to improve the temperature homogeneity. A new ferromagnetic insert will be used to improve the compensation accuracy. Experiments with quickly varying gravity imposed by a new electric power supply are planned. Eventually, experiments near the oxygen critical point will be carried out to study the mechanism of the boiling crisis (Critical Heat Flux, CHF) studied earlier in a very small hydrogen cell [7].

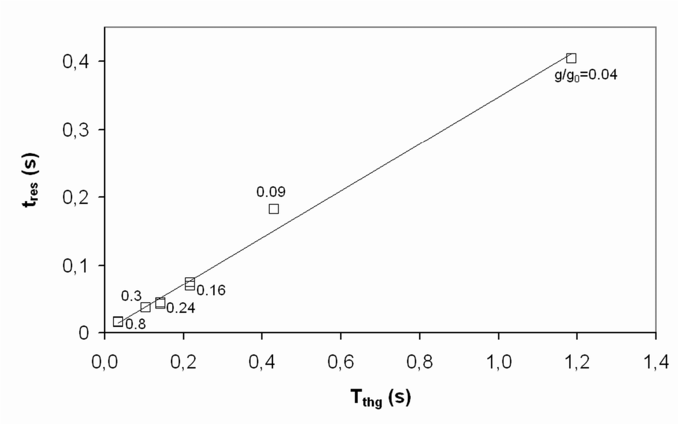

Fig. 7: Departure period vs. thermal growth time. The gravity level for each point is shown.

Acknowledgements

This work was partially supported by CNES and Air Liquide Company.

We would like to thank Patrick BONNAY, Sylvain BRESSIEUX, Jérôme CHARTIER, Daniel COMMUNAL, Jean-Marc MATHONNET and Jérôme LACAPERE for their contribution.

References

[1] R. Wunenburger, D. Chatain, Y. Garrabos, D. Beysens, Phys. Rev. E 62, 469-476 (2000)

[2] D. Chatain, V.S. Nikolayev, Cryogenics 42 253–261 (2002).

[3] D. Chatain, D. Beysens, K. Madet, V. Nikolayev, A. Mailfert, Microgravity sci. Technol. XVIII-3/4 196-199 (2006).

[4] L. Quettier, H. Félice, A. Mailfert, D. Chatain, D. Beysens, Eur. Phys. J. Appl. Phys. 32, 167-175 (2005).

[5] C. Brennen, Fundamentals of Multiphase Flow, Cambridge University Press (2005).

[6] D.M. Qiu, V.K. Dhir, et al., J. Thermophysics and Heat Transfer, 0887-8722 vol.16 no.3 (336-345), 2002.

[7] V.S. Nikolayev, D. Chatain, Y. Garrabos & D. Beysens, Physical Review Letters 97, 184503 (2006).