MAGNETIC FACILITY GIVES HEAT TRANSFER DATA IN H_2 AT VARIOUS ACCELERATION LEVELS

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CENTRE NATIONAL D'ETUDES SPATIALES

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ABSTRACT

A large vertical magnetic field gradient, as provided by a 10 T superconductive coil, induces a volume force that acts on hydrogen diamagnetic atoms. This force is additive to gravity. It is therefore possible to vary the effective gravity acceleration. A set-up is presented where an effective acceleration between –0.2 g and 1 g can be obtained in H_2, including weightlessness (g is the Earth gravity). As an example, heat transfer measurements, including boiling, are reported at various acceleration levels, near the critical point (33K, 1.3 MPa) and at 20.7 K, 0.15 MPa..
Such set-up can be used to obtain thermal data without experimenting in space. A project to study O_2 under paramagnetic compensation will also be presented.

1. INTRODUCTION

We aim to model both experimentally and theoretically the heat transfer in fluids under effective gravity acceleration which is variable between –0.2*g* and 1*g* (*g* is the Earth gravity). Applications to cryofluids used in spacecraft engines follow directly.

We elaborated a technique of magnetic gravity compensation [1-3]. Its principle [4-5] is based on the fact that in an inhomogeneous magnetic field **B**, a force proportional to μ.grad($\mathbf{B}^2$) acts on each hydrogen (diamagnetic) atom with a magnetic susceptibility μ just like the gravity does. We use a superconductive 10T coil, near an extremity of which the field is inhomogeneous. Therefore, the total (gravity + magnetic) force can be zero or even directed against the gravity. The value of this force is defined by the field configuration so that a given acceleration value (e.g. zero) can be achieved in a single point. One can determine the volume surrounding this geometrical point in which the given non-uniformity of the total acceleration is not exceeded. Using the above coil, the gravity can be compensated with the accuracy ±0.01 g in the volume of 2 x 2 x 10 mm^3 or ±0.015 g in a cylinder 16 mm long and 3 mm diameter. This technique can be applied also to study the paramagnetic O_2.

The second important feature of our work is a possibility to study heat transfer. We consider first the near-critical region of the phase diagram of H_2, i.e. around its critical point, see Fig.1, where fluids are extremely sensitive to gravity. The "critical slowing down" [6] observed in this region permits the detailed observation of heat transfer phenomena that are extremely fast in other conditions, like bubble growth during boiling or boiling crisis [7-9]. Since the physical parameters of fluids change strongly with temperature in this region, temperature has to be rigorously stabilized. Another situation of interest is heat transfer around 20K and 0.15 Mpa, including boiling. Using such experiments, heat transfer parameters for H_2 can be obtained at various gravity levels and the physics of boiling better understood.

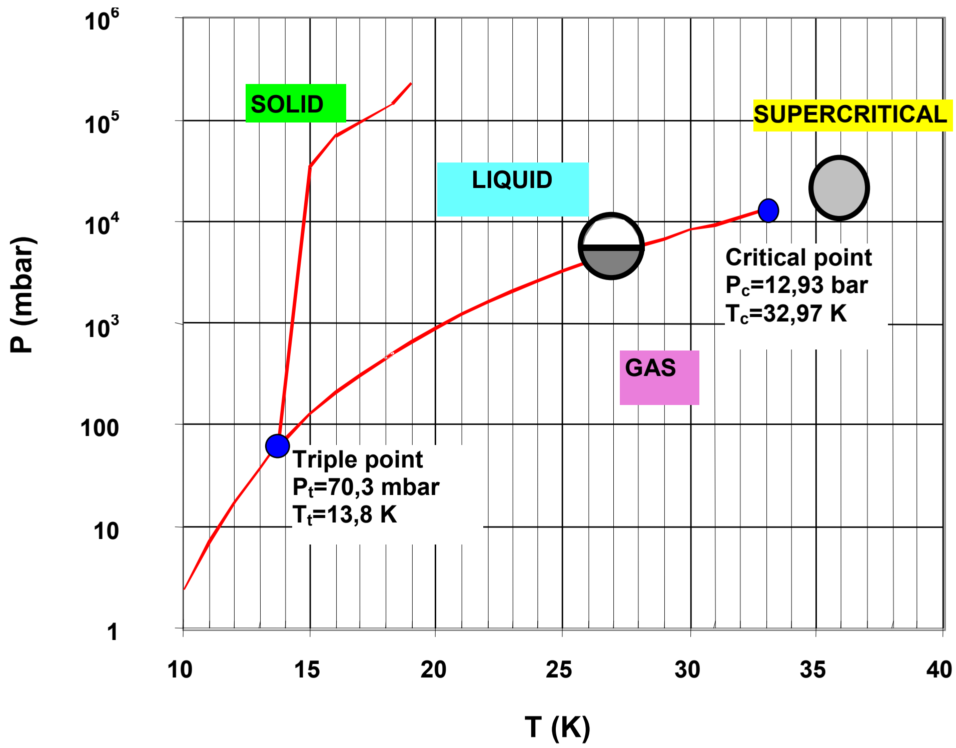


Fig.1. Phase diagram of H_2 in pressure –temperature coordinates.

2. EXPERIMENTAL SETUP

The cryostat (Figs.2a-b) is a cylinder of 300 mm diameter and 1300 mm height. It contains a superconductive coil immerged into a liquid helium bath at 2.17K. The value of the electric current in the coil can be controlled to adjust the magnetic force, i.e. to create a given effective gravity acceleration. Since the magnetic force is material-dependent, the effective gravity acceleration depends on the material too. We used exact gravity compensation (zero effective gravity acceleration) in most of the experiments. The residual acceleration map for this case is shown in Fig.3.

The experimental cell and the other apparatus are located inside the vacuum chamber (see Fig.2a) which provides the thermal contact with the helium bath. The transparent cell is illuminated by a light guide. Another light guide (endoscope) delivers the cell image to the CCD camera for visualization and recording. The cell can be vibrated, however, we do not report here about this feature. The cell temperature can be varied between 10K and a temperature T_x limited by the pressure in the cell (here 2 MPa). The latter corresponds to T_x = 37 K for a cell filled at the critical density of H_2.

The cell is filled *in situ* by a capillary. When the needed fluid volume is obtained, the cell is isolated from the capillary by an ice toe formed inside the capillary by freezing the thermal valve.

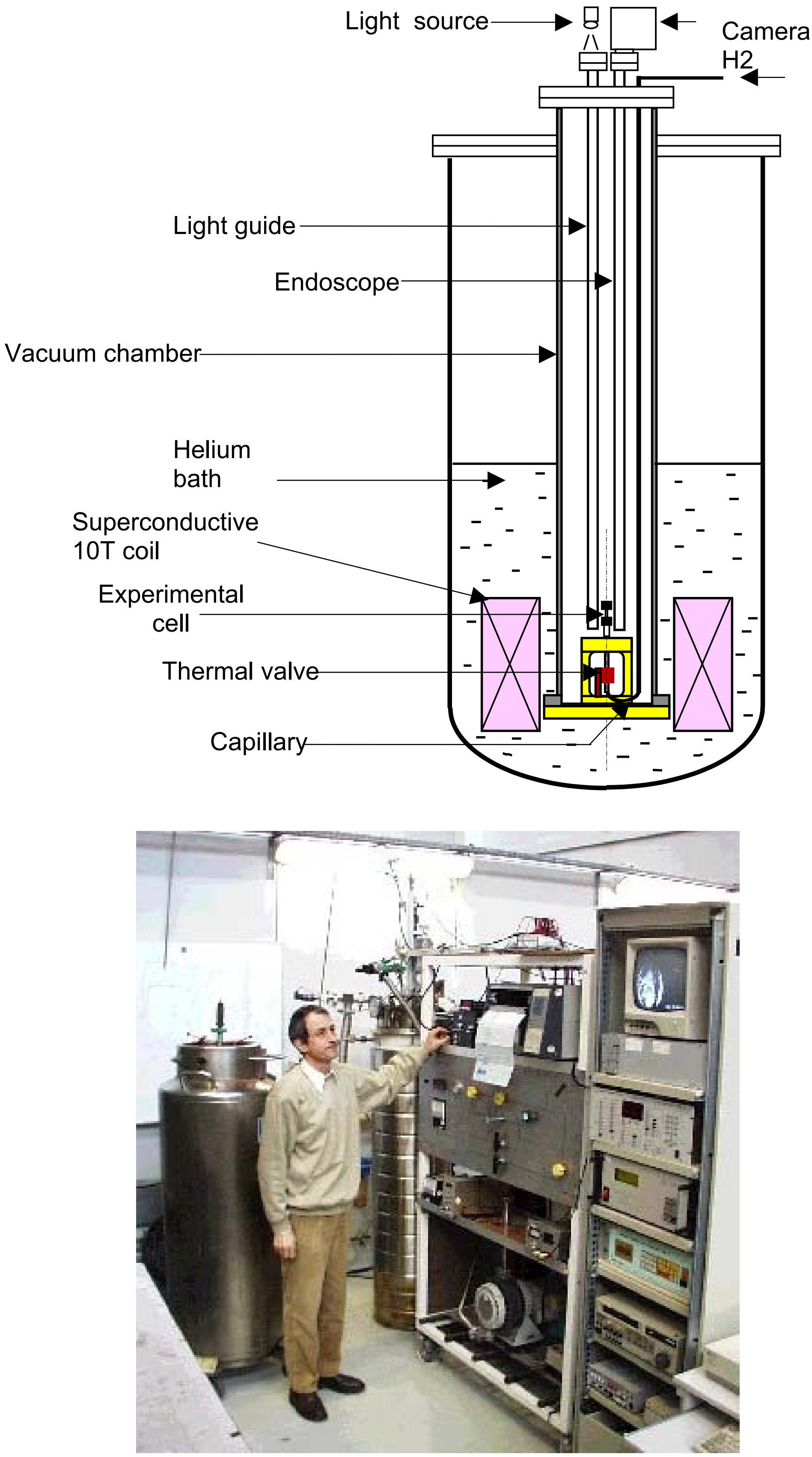


Fig. 2. (a). Scheme of the experimental setup. (b) Photo of the experimental setup

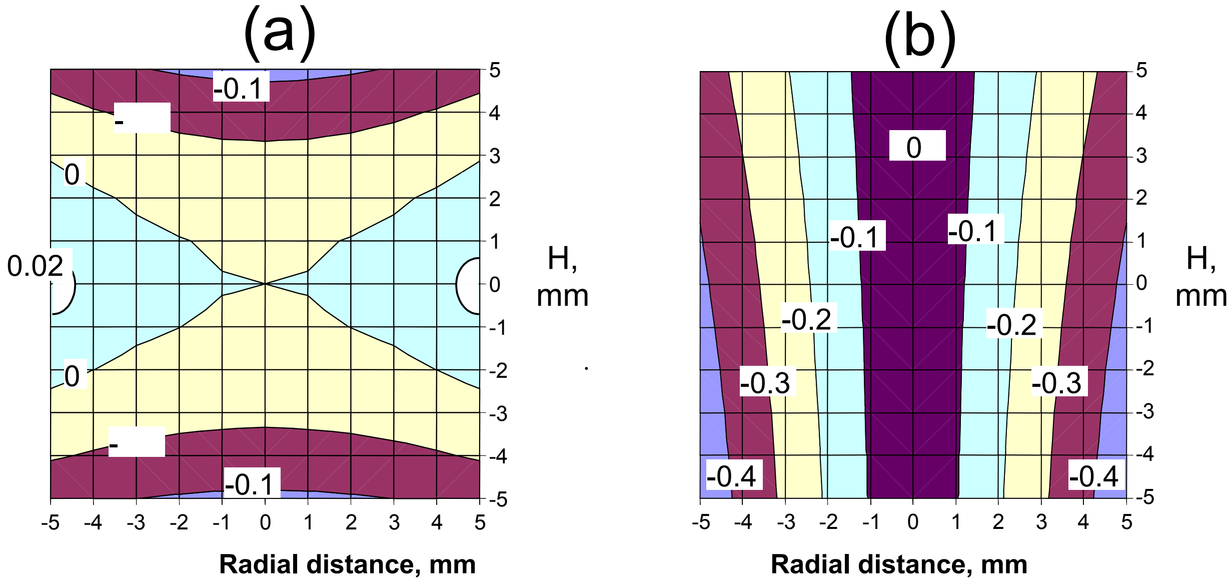


Fig.3. Iso-acceleration curves for the vertical (a) and radial (b) components of the total acceleration at gravity compensation of H_2. The acceleration values are given in m/s^2.

We will discuss here the study performed with a thermal flux cell (see Fig. 4) made as a tube 16 mm long and 3 mm of internal diameter. The cell is positioned along the coil axis. The cell center coincides with the point of exact gravity compensation. These conditions were chosen to provide a low level of residual gravity acceleration, within 1.5 10^{-2} g. The tube is made of Polymethylmethacrylate (PMMA, commercial name *Plexiglass*). This material was chosen because it is transparent and has a small thermal conductivity. Both ends of the tube are closed by copper flanges, each incorporating a resistive heating element and a resistance thermometer (*Cernox,* from Lakeshore).

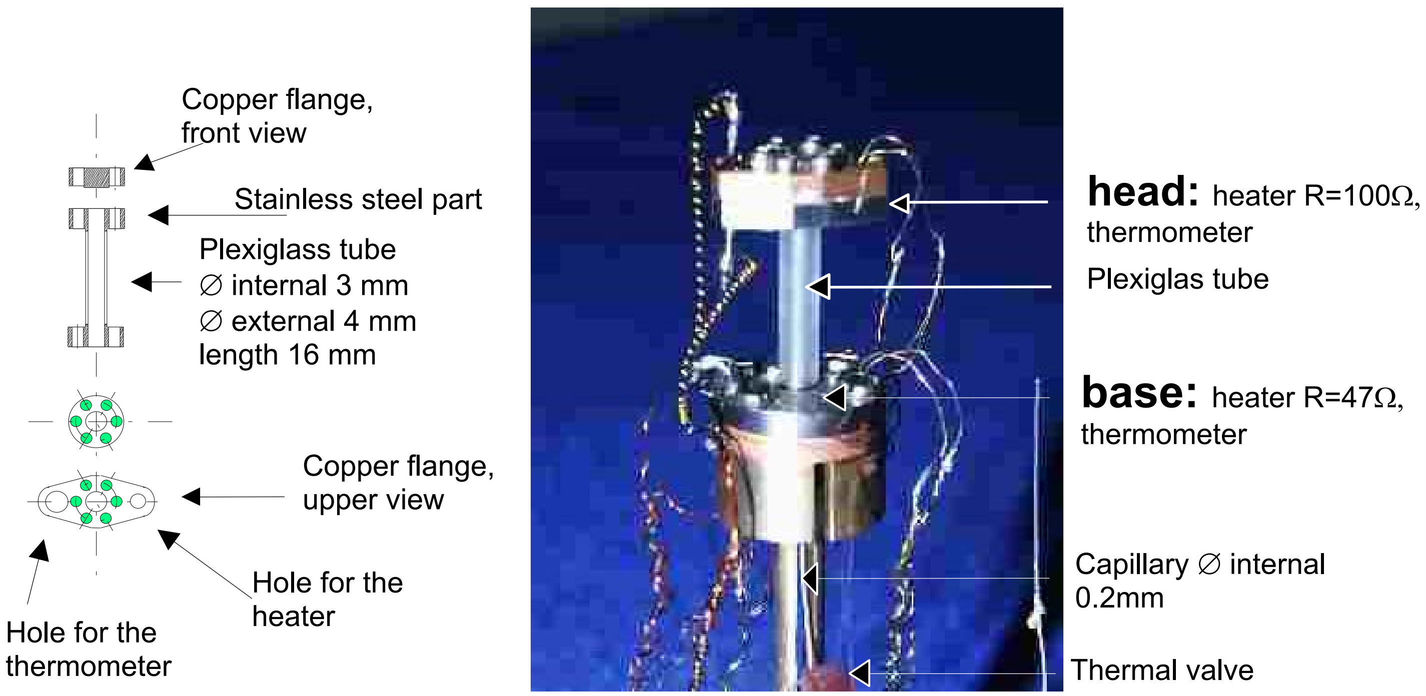


Fig.4. Scheme and photo of the cell.

The base of the cell is thermally connected to the helium bath through the cell support, which provides a thermal resistance. In order to cool the cell head, a thin copper wire (section: 0.5 mm^2, length 20 cm) connects it to the helium bath. To work near the critical point (see Fig.1 and the associated discussion), we stabilize the temperature of the cell at about 33 K by supplying the heating power P^0_H =10 mW to the cell head and P^0_B =160 mW to the cell base. These values serve as a reference level for the power supply values. The temperature of the base is regulated within 0.3 mK accuracy by a numerical thermal regulation *Linear Research*. The cell head is heated by a stabilized power supply.

3. EXPERIMENTAL PROCEDURE FOR HEAT TRANSFER MEASUREMENTS.

3.1. Study of heat transfer in homogeneous (supercritical) region at constant volume

The experimental procedure is as follows (Fig.5):

- The cell is filled under low gravity ($\approx$ 0.2 g, to make flat the gas-liquid interface near T_c) at a stabilized temperature $T \leq T_c$. The visual determination of the meniscus position allows the cell density to be determined. Pressure can then be determined from the equation of state. The cell is then closed by sealing the capillary with the thermal valve. The level of wanted gravity is adjusted. It is possible to vary the effective gravity between 1g and –0.2g by varying the coil current. It is also possible to vary the effective gravity between –1g and +1g by exchanging the roles of the head and base of the cell.
- The fluid is initially isothermal at a stabilized temperature $T_i > T_c$, i.e. the fluid is supercritical and homogeneous. The temperatures of the head (T_H) and of the base (T_B) are identical $T_H = T_B = T_i$.
- At the time t=0 a supplementary power P_H is injected into the head. The base temperature is maintained at $T_B = T_i$ by the temperature regulation.
- The evolution of the temperature $T_H(t)$ and of the power $P_B(t)$ injected to the base by the temperature regulation necessary to maintain $T_B = T_i$ are recorded. The difference $P_t(t) = P^0_B - P_B(t)$ measures the transferred heat flux.

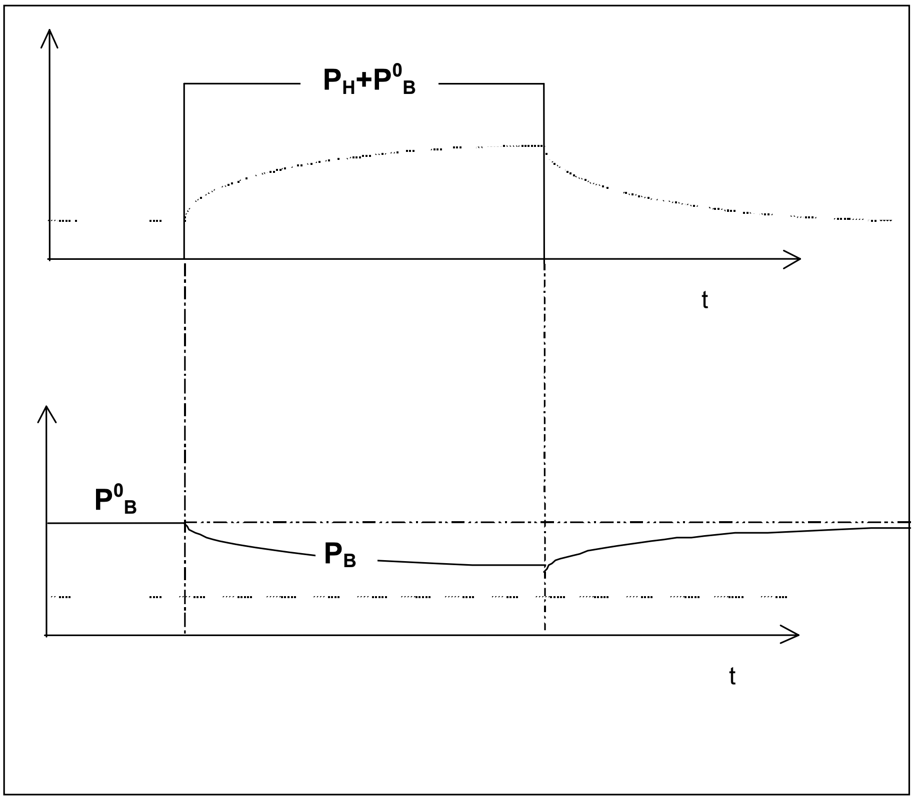


Fig.5. The experimental timeline (schematic).

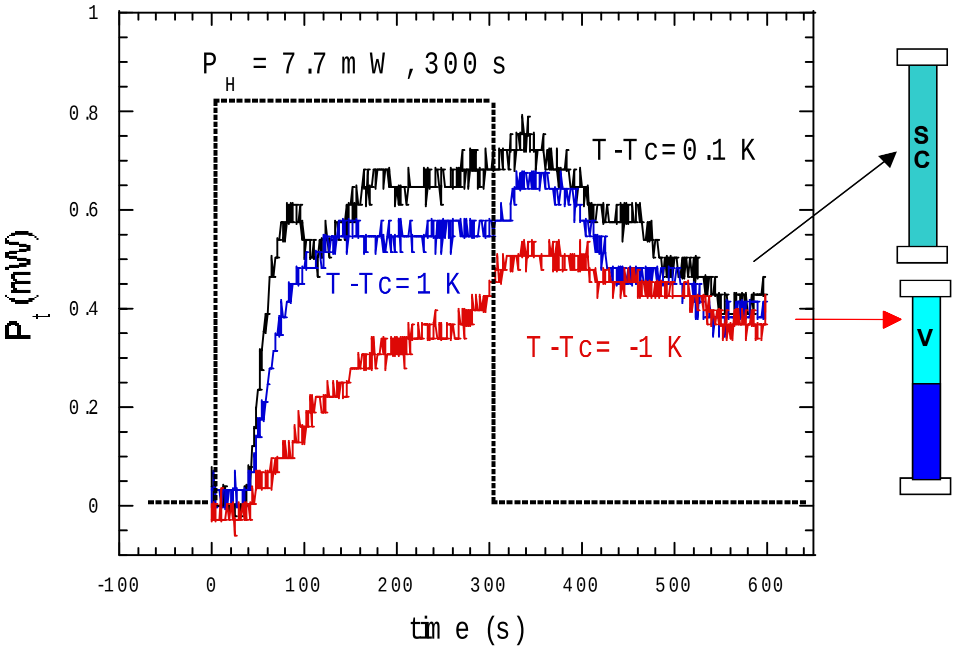


Fig.6. The heat power $P_t(t)$ *transferred to the base from the head after the injection of the power* $P_H = 7.7$ mW *during* 300 *s at normal gravity. Different temperature from the critical temperature (Tc = 33 K) are shown. Oscillations, due to convections, are observed*

The results for a constant volume cell at normal gravity are shown in Fig.6. The cell is at critical density and (i) supercritical ($T-T_c$ = 0.1K and 1K) or (ii) subcritical, in the two-phase region ($T-T_c$= -1K). The sample was heated from above to minimize the convection; however, oscillations are clearly seen, which corresponds to visual observation of convection. In the two-phase regime, the gas phase is in the thermal contact with the heater, so that the heat exchange is weaker.

An example of data obtained at gravity compensation is shown in Fig.7. Although the transfer is fast, no convections are observed. The oscillations have disappeared. The heat transfer under these conditions is due to a compressibility effect (the "piston effect") [10] and can be calculated by efficient numerical methods [11-12].

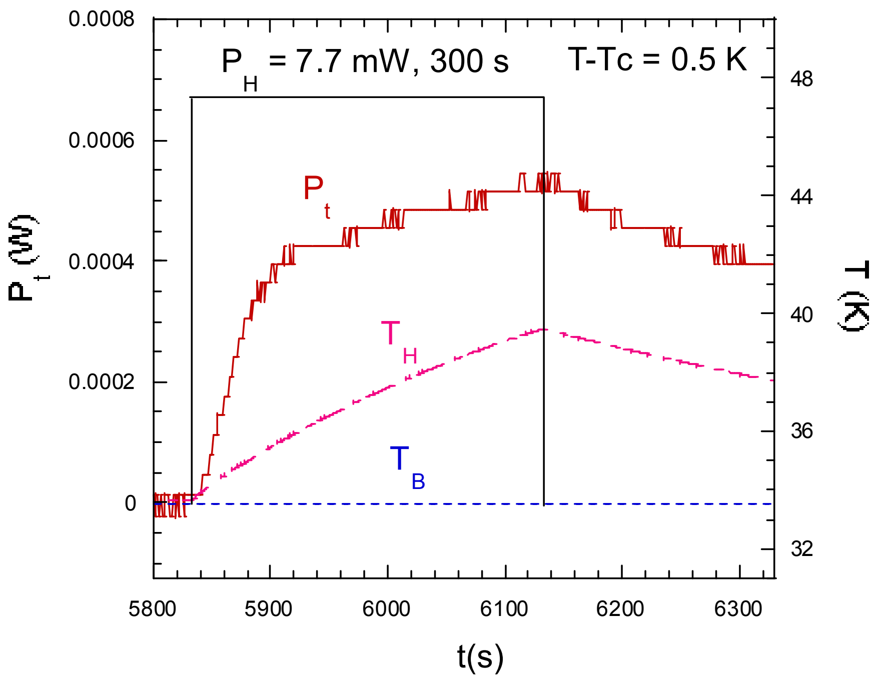


Fig.7. Example of heat transfer data obtained under « 0g ».

3.2. Preliminary study of nucleate boiling.

In this configuration, the thermal valve is left open and the sample remains connected through the capillary to a large buffer volume (1 dm^3) at room temperature. The pressure thus remains nearly constant during heating. The experimental procedure is as follows:

- -Initial isothermal state: $T_i<T_c$. Hydrogen is in the homogeneous liquid state because temperature T_i is chosen to be slightly smaller than the saturation temperature T_s for the chosen cell pressure: $T_i = T_s -$ □□
- -At time t = 0 a power P_H is injected into the head. The base temperature is maintained at $T_B = T_i$ by the temperature regulation.
- -The evolution of the temperature $T_H(t)$ and the power $P_B(t)$ injected to the base by the temperature regulation necessary to maintain $T_B = T_i$ are recorded. The difference $P_t(t)= P^0_B - P_B(t)$ measures the transferred heat flux.
- -Visual observation of boiling phenomena at the head – fluid interface.

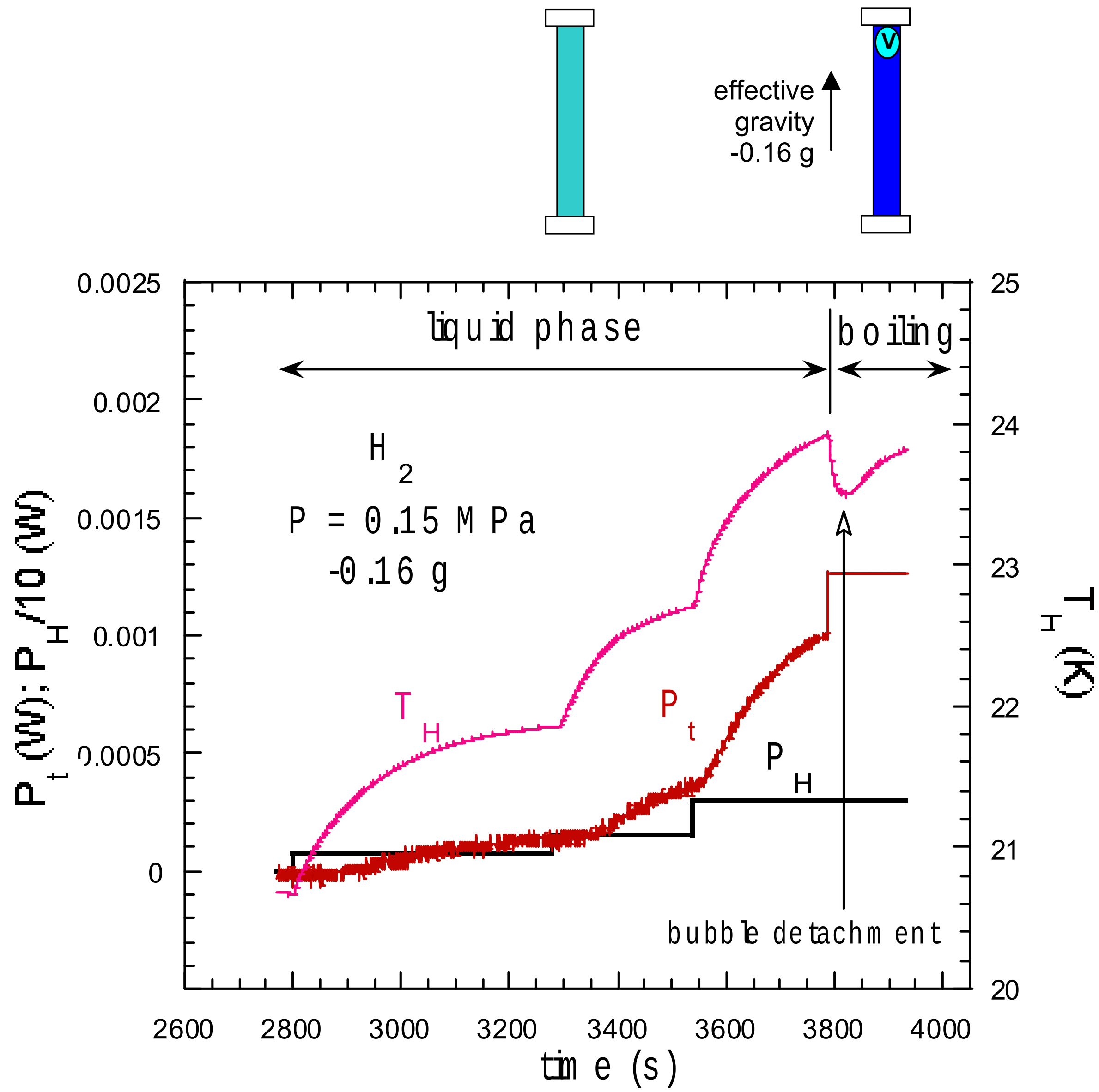


Fig.8. Thermal behavior around 20K under « - 0.16 g ». When boiling occurs, the bubble detaches from the hot wall. (The saturation of P_t at 1.3 mW is caused by the temperature regulation system).

The temperature rise of the head and the correlated transmitted power to the base are shown in Fig. 8 when the heating power increases. The effective gravity was tuned to be weak (- 0.16 g) and directed towards the head. Weak convections are observed. When boiling occurs, the bubble detaches from the head and the transmitted heat flux rises. The head temperature oscillates as due to the growth and detachment of the bubble.
The heat transfer can be illustrated in a P_t – T_H diagram (see Fig.9). It resembles the boiling curve [13]. However, unlike the boiling curve, it was not obtained under fully stationary conditions.

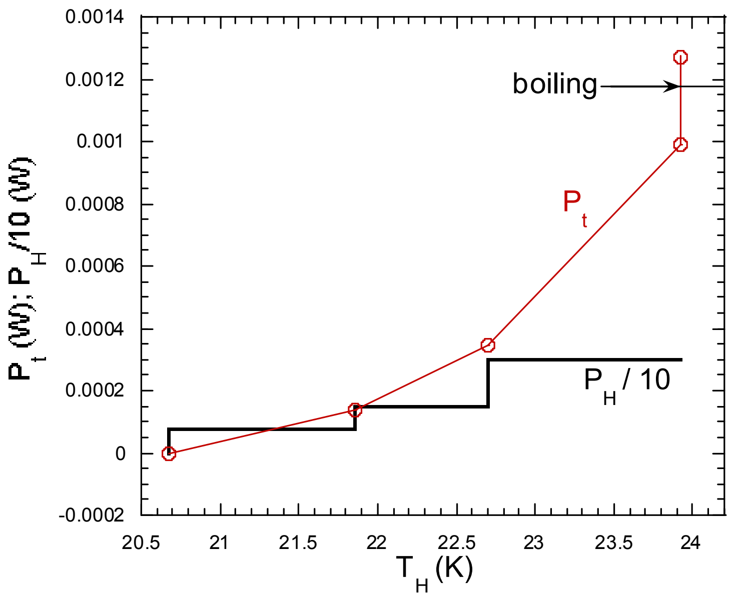
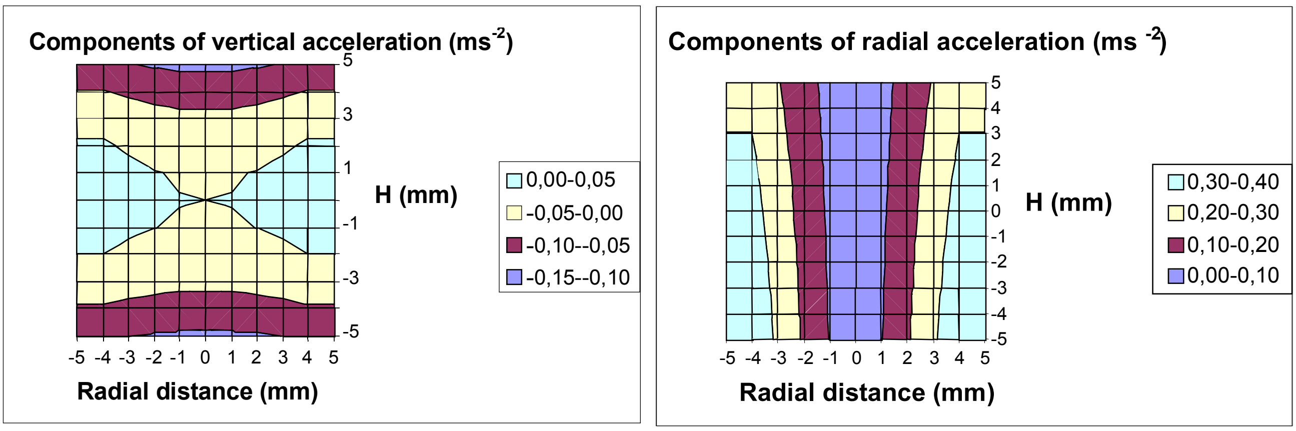


Fig.9. A boiling-like curve: correlation between the transmitted power (Pt), the power sent in the head (P_H) and the head temperature (T_H) under near-steady conditions.

4. A STUDY WITH OXYGEN

The above studies can also be performed with O_2 after some modifications of the magnetic set-up. It is somewhat easier to compensate gravity in O_2 as this element exhibits a very large (para)-magnetic susceptibility. The cell should be placed in the lower part of the coil, at 85 mm from the coil center. The product of the field by the gradient of field must be $9T^2m^{-1}$ for exact gravity compensation. This is obtained in our coil with a current of 1.287 A (maximum field at the coil center: 1.279 Tesla. Fig.10 below shows the



residual accelerations.

Fig.10. Residual acceleration with a cell filled with O_2.

5. COMPENSATION OF MORE IMPORTANT SAMPLE VOLUMES

To compensate gravity in a larger volume, it is necessary to have a greater homogeneity of the product (field) x (field gradient). Theoretical studies [4-5] and recent experiments show that it is possible to calculate special ferromagnetic inserts and /or dipole-like coils that provide the required magnetic configuration. As an example, homogeneity of compensation inside a cylinder of 1 m length and 10 mm diameter is expected to be less than 0.01g.

6. CONCLUSION

We report heat transfer and visual studies with H_2 samples under zero and weak gravity levels as provided by a magnetic compensation device. Magnetic compensation of gravity forces enables an effective variable gravity, including zero-gravity, to be applied to heterogeneous samples. Compensation appears as an interesting alternative mean to represent the space conditions on a pure – but density inhomogeneous – fluid sample. The quality of the compensation is limited by the uniformity of the product (field) x (field gradient). Using a simple coil and H_2, the compensation quality remains within 0.015 g for samples of 16 mm length and 3 mm diameter. It is worthy noting that much larger samples could be studied by using inserts and/or magnetic dipoles. Compensation in O_2 is envisaged and is technically easier to perform than with H_2.

REFERENCES

1. R. Wunenburger, D. Chatain, Y. Garrabos, D. Beysens, “Magnetic compensation of gravity forces in (p-) Hydrogen near its critical point ; application to weightlessness conditions”, Phys. Rev. E **62**, 469-476 (2000).
2. Web site: http://www-drfmc.cea.fr/SBT/ESEME/documents-eseme-ang.htm
3. D. Chatain D., V. S.Nikolayev, « Using magnetic levitation to produce cryogenic targets for inertial fusion energy: experiment and theory », Cryogenics, **42**, 253 – 261 (2002).
4. L. Quettier, A. Mailfert, “New Design of Superconducting Magnet For Generation, of Quasi-Uniform magnetic Force Field ”, Procedings of the Applied Superconductivity Conference, Houston USA (4-9 Aug. 2002).
5. L. Quettier, A. Mailfert, “2-D Inverse problem : Ideal current distribution generating a magnetic force field with given constraints on homogeneity ”, Procedings of the VII-th International Workshop on Optimization and Inverse Problems in Electromagnetism, Lodz, Poland (12-14 Sept. 2002).
6. H.E. Stanley, “ Introduction to Phase Transitions and Critical Phenomena”. Oxford, Clarendon Press (1971).
7. V. S. Nikolayev, D. Beysens. “ Boiling crisis and nonequilibrium wetting transition ”, Europhys Lett. **47**, pp.345-351 (1999)
8. V. Nikolayev, D. Beysens, G.-L. Lagier, J. Hegseth, “Growth of a dry spot under a vapor bubble at high heat flux and high pressure”, Int. J. Heat & Mass Transfer **44**/18, pp 3499-3511 (2001)
9. Y. Garrabos, C. Lecoutre-Chabot, J. Hegseth, V.S. Nikolayev, D. Beysens, J.-P. Delville, “Gas spreading on a heated wall wetted by liquid”, Phys. Rev. E **64**, 051602-1 – 10 (2001)
10. Y. Garrabos, M. Bonetti, D. Beysens, F. Perrot, T. Fröhlich, P. Carlès, B. Zappoli “ Relaxation of a supercritical fluid after a heat pulse in absence of gravity effects. Theory and experiments ” Phys. Rev. E. **57**, pp. 5665-5681 (1998)
11. V.S. Nikolayev, A. Dejoan, Y. Garrabos, D. Beysens « Fast heat transfer calculations in supercritical fluids versus hydrodynamic approach » (submitted to Phys. Rev. E, Nov. 2002)
12. D. Beysens, D. Chatain, V.S. Nikolayev, Y. Garrabos, A. Dejoan, « Fast heat transport under weightlessness » (preprint, 2002)
13. L. S. Tong, “Boiling Heat Transfer and Two- Phase Flow”, Taylor & Francis, New York (1997), 2nd ed.