EXPERIMENTAL AND NUMERICAL STUDY OF THERMOCAPILLARY CONVECTION AROUND A SINGLE AIR OR VAPOUR BUBBLE ON GROUND AND IN MICROGRAVITY

P.Cerisier, M. Barthès, R. Santini, D. Veyret and L.Tadrist
Polytech Marseille, UMR CNRS 6595, University of Provence, 5 Rue Fermi, 13397 Marseille cedex 13, France

Abstract

One studies the influence of the Marangoni effect on the heat transfer around a bubble of air on the ground and in microgravity. This transfer is enhanced in microgravity. According to the value of the Prandtl number of the liquid in convection, oscillatory states around the bubble are observed as well on the ground that in microgravity. Similar experiments are carried out on a growing vapour bubble. Characteristics of the threshold between stable and oscillating states are given. Results obtained from numerical study performed with the method of finite elements method are in agreement with experimental results.

INTRODUCTION

The industrial processes utilizing the interfaces are very numerous in chemical engineering and in technologies of changes of state. Optimization of the heat transfers is often the primordial objective. . Among them, boiling, although very largely used in industry is still very badly known. A lot of scientific works are being performed to study the mechanism of boiling. With the latest experimental results of pool boiling obtained under microgravity, this mechanism seems to be efficient to transfer heat [1,2] under microgravity as under normal gravity. These results are in contradiction with classical theories [3] which explain the importance of the heat transfer under normal gravity with bubble detachment induced by the buoyancy force. To understand why the gravity level has little influence on heat transfers induced by boiling and to determine which phenomenon is responsible for this equivalence, new kinds of experiment have been performed in the last years. They are carried out around a single bubble [4,5] to avoid interactions with other bubbles and without a phase change to avoid interactions between the different phenomena. In this study we present two kinds of experiments around a single bubble: 1/-The first one concerns the Marangoni effect. It is studied separately because it is independent of the gravity level and could play an important role under microgravity [6]. To isolate this phenomenon, we consider an air bubble without phase change; 2/-The second one concerns the growing of a single vapour bubble on an artificial nucleation cavity. Experiments were performed on ground and in microgravity (parabolic flights). For liquids with a low Pr, we observed as already mentioned previously by different authors a steady thermocapillary convection followed by an oscillatory state when a critical threshold is exceeded [2]. The steady state has been studied by several authors [2,7]. There are very few works on the oscillatory state. Consequently we study in particular this state under normal and reduced gravity.

A. AIR BUBBLE (without phase change)

1. EXPERIMENTAL SET-UP

The test chamber has a cavity with an inner square section (40 mm × 40 mm) and a variable height H. This cavity is completely filled with a silicone oil layer, whose Prandtl number (Pr) is equal to 16.7 or to 220 (Table 1). A vertical temperature gradient is established within the silicone oil layer by heating the upper horizontal wall and by cooling the lower one. With this thermal configuration, a steady conductive state can be reached without a bubble. When the steady conductive state is reached an air bubble is injected under the upper heated wall through a hole at the centre. The chamber is completely transparent to visualize the phenomenon simultaneously in the horizontal and vertical planes. The cavity is made of Plexiglas. H is equal to 5 mm. Above and below the cavity, there are two cells which are maintained at a fixed hot and a fixed cold temperature respectively by means of two thermostatic circulation baths in order to establish the temperature gradient.

The associated experimental set-up consists of a 25 image-per-second video-camera with a macro-zoom, two parallel light beams and three mirrors in order to observe the phenomenon in the vertical and horizontal planes with only one video-camera. Because of standards and experimental constraints concerning the fluid on board an Airbus A300 (water tightness, quantity …), this test chamber was used only on the ground. A second test chamber was used for parabolic flights allowing only visualisation in vertical plane. Shadowgraphy has been used to observe the temperature field in the vicinity of the bubble only into the vertical plane under normal and reduced gravity conditions. Tracer particles were also used to observe the velocity field. To measure the frequency of the oscillatory mode, a photodiode sensor was coupled with this optical method. Experiments in microgravity have been realized under reduced gravity during parabolic flights.

2. EXPERIMENTAL RESULTS

2.1. Structure of the oscillatory thermocapillary convection state and the associated frequency (Pr=16,7).

In the case of Pr = 220, the oscillatory state never occurred. Under normal gravity the frequency of the oscillatory mode (Fig.1) has been determined versus the bubble size, the temperature gradient in the case Pr =16,7 around the air bubble to study the influence of the gravity level on the 3D periodic thermocapillary state. It is shown that the frequency of the oscillations decreases.

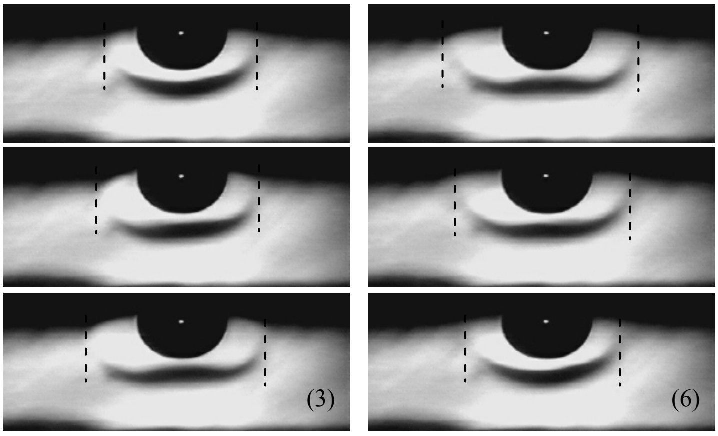


Fig. 1. Photographs showing in a vertical plane by shadowgraphy an oscillatory mode under normal gravity

But visualisation only in the vertical plane, is not sufficient to determine if this oscillation corresponds to a 3D structure with extrema and minima which turn around the bubble. Observation in a horizontal plane makes evident that the thermocapillary roll is distorted periodically. It can be seen on figure 2a for the stationary state that the particles are on a circle, the thermocapillary roll is axisymmetrical and on figure 2b the oscillatory state. There are two extrema which turn around the bubble. The number of extrema depends on the operating conditions (the bubble size and/or the temperature gradient). For instance two examples can be seen in the figure 2: (a) corresponds to 2 extrema (wave number is 2), (b) corresponds to 3 extrema (the wave number is 3).

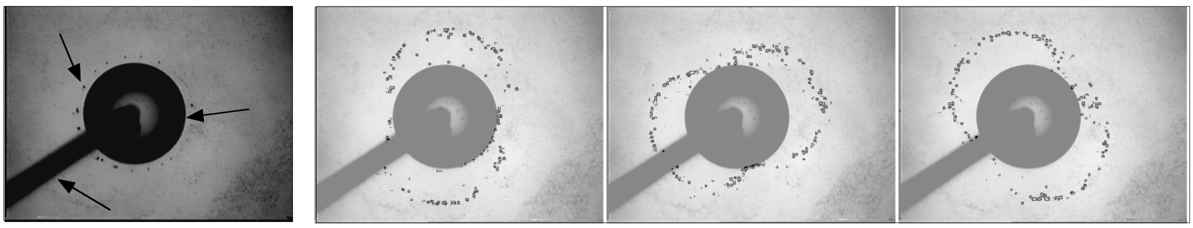


Fig. 2. Photographs showing in a horizontal plane by means of tracer particles injection
(a) the steady state (bubble radius Rb : 3,8 mm, gradient : 1300 K/m); (b) the oscillatory mode every 1,04 s (Rb = 3,1 mm, gradient 2100 K/m). The air injector is located in the horizontal heated wall made of Plexiglas

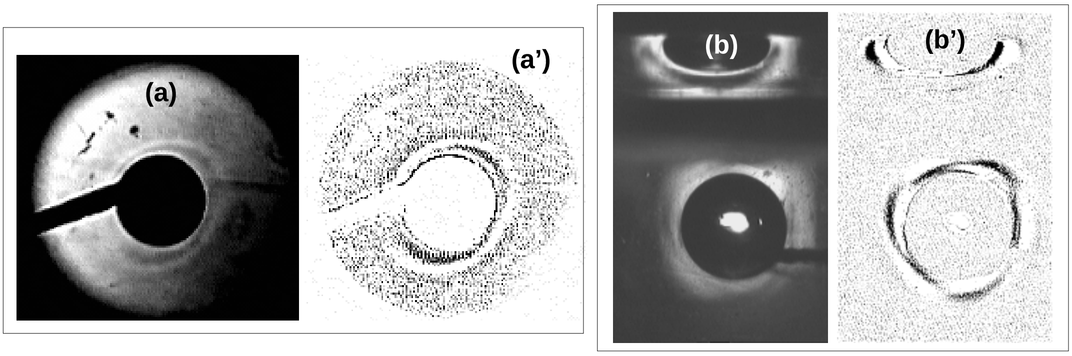


Fig. 3. Photographs showing the 3D oscillatory mode by shadowgraphy with and without numerical processing: (a-a') : in a horizontal plane with a wave number equal to 2 (Rb = 3,6 mm, gradient 1.9 K/mm). (b-b'): in the horizontal and vertical planes with a wave number equal to 3 (Rb = 4,1 mm, gradient 3.3 K/m)

2.2. Heat transfer induced by the thermocapillary convection (Pr=16,7)

During a second campaign of parabolic flights we studied the heat transfer induced by thermocapillary convection under reduced gravity conditions

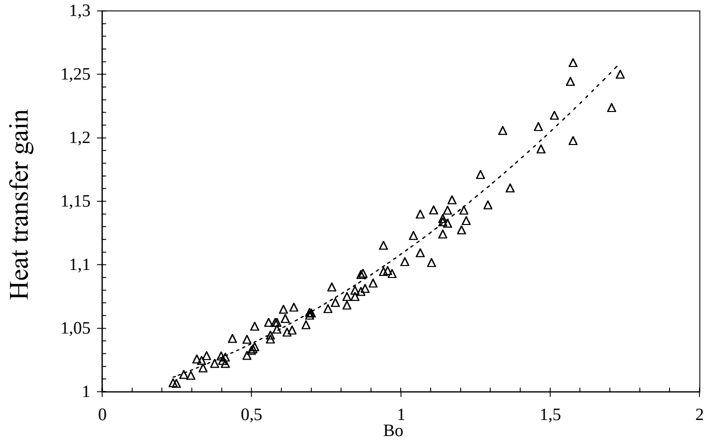


Fig. 4. Heat transfer gain versus the Bond number under normal gravity (Pr =16,7)

These experimental works have been performed with the same operating conditions (bubble size, temperature gradient, Prandtl number) that under normal gravity. Two different behaviours have been determined. On ground the heat transfer gain depends on the Bond number, and under reduced gravity conditions it depends on the Marangoni number. The heat transfer enhancement corresponds to the ratio between the heat transfer with a bubble to the heat transfer without any bubble in the liquid layer. On the other hand heat transfer gain can reach 3,2 under reduced gravity whereas under normal gravity the maximum heat transfer is 1.3. Finally, we have observed that the nature of the state of thermocapillary convection, for the low Prandtl number, does not change the heat transfer.

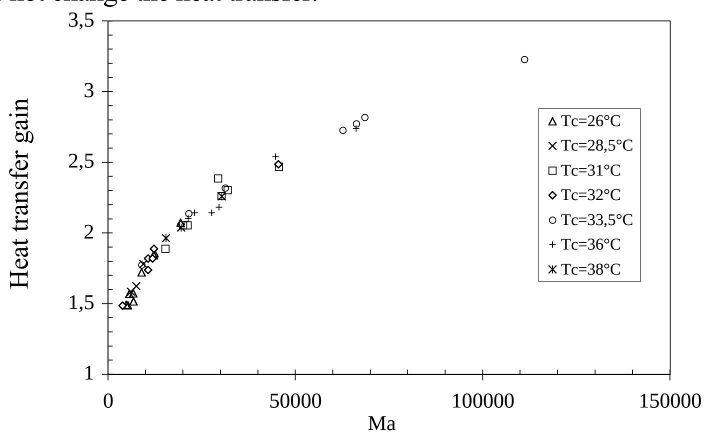


Fig. 5. Heat transfer gain versus the Bond number under reduced gravity (Pr =16,7)

3 – MATHEMATICAL MODEL AND PHYSICAL CONDITIONS

The model takes buoyancy and thermocapillary effects into account. The fluid is treated as a Boussinesq one with constant physical properties except for the buoyancy term where the density is allowed to vary. Themocapillary flows are driven by the variation of surface tension with temperature which is assumed to obey to the linear relation: $\sigma = \sigma_0 - \gamma\,(T\text{-}T_0)$. The problem is made nondimensional. We use the tree classical equations

$$\nabla \cdot \mathbf{u} = 0 \quad ,$$

$$\frac{\partial \theta}{\partial t} + \mathbf{u} \cdot \nabla \theta = \frac{1}{Re\,Pr} \nabla^2 \theta \quad ,$$

$$\frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla \quad = \frac{1}{Re\,Pr} \nabla^2 \quad .$$

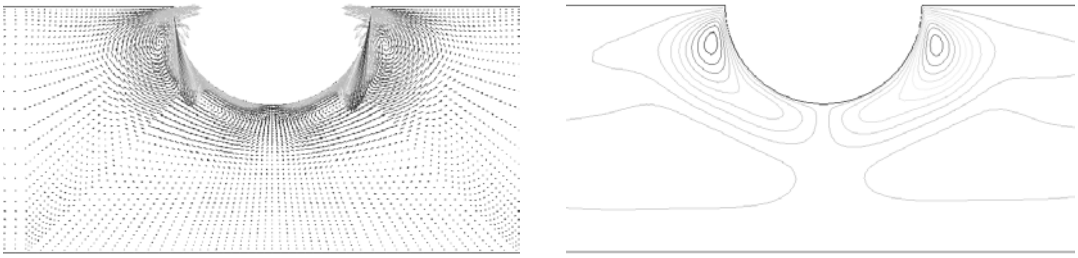
The Reynolds, Prandtl and Grashof numbers are defined according to

$$Re = \frac{\gamma \Delta T R}{\nu \mu} \qquad Pr = \frac{\nu}{\alpha} \qquad \mathrm{G}r = \frac{\beta g \Delta T R^3}{2} \quad .$$

The thermal conditions are: fixed temperatures at the top and bottom walls whereas the free surface and the outer wall are adiabatic. The velocity conditions are no-slip at the top, bottom and outer walls. The free surface is assumed undeformed. Surface tension variations on the free surface give rise to the thermocapillary coupling between shear stress and temperature gradient. The finite element method is used to solve the system of equations.

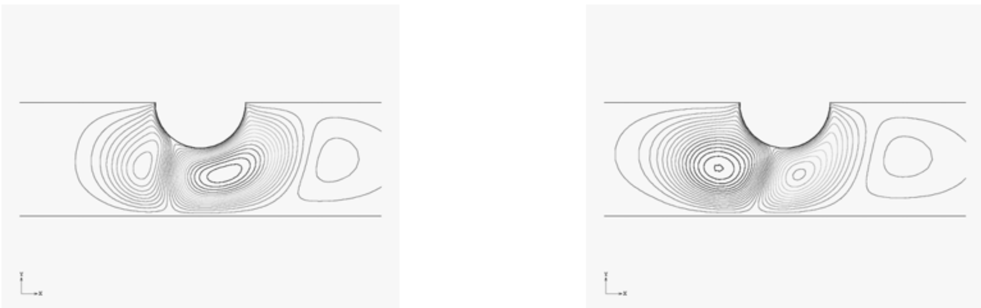
4. NUMERICAL RESULTS

The first results were obtained for a 2D geometry. For a Pr =17 and a Re = 1000, the 2D system gives a steady solution (Fig. 6). However under microgravity conditions, if we increase the Reynolds to 6000, the system starts oscillating (Fig. 7). A movie shows the calculated oscillations during the presentation.



Vectors Streamlines

Fig.6. Steady state - Re = 1000 - Pr = 17



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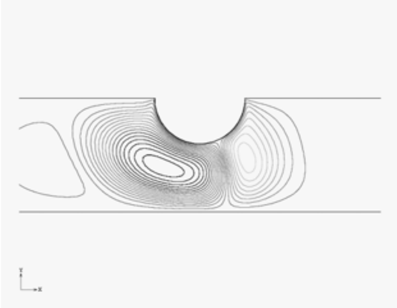 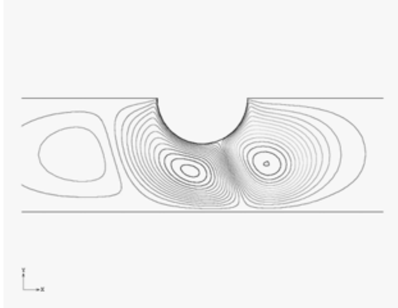

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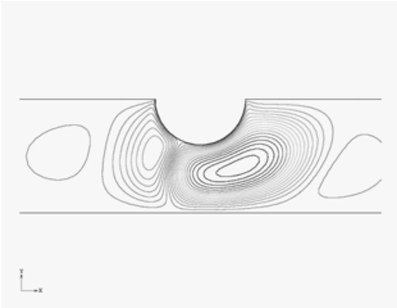
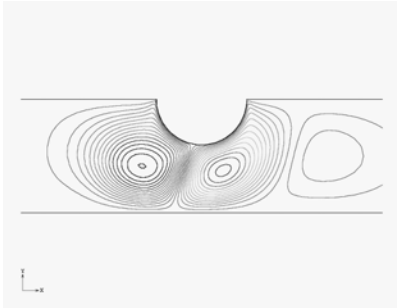
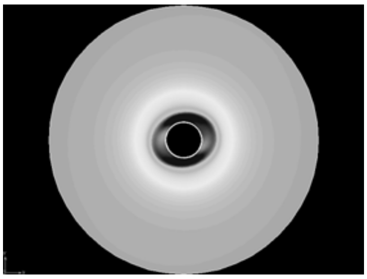
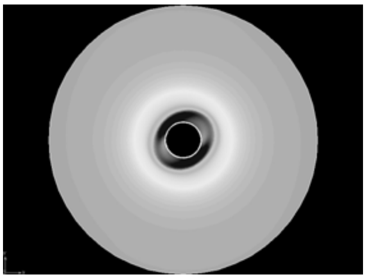
 

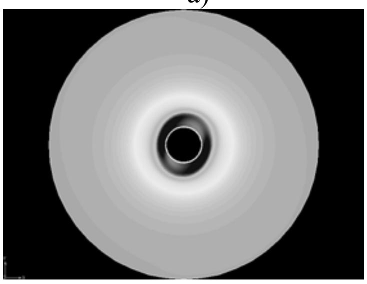
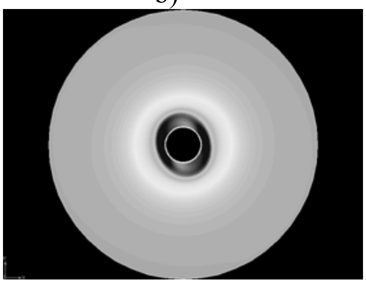
e f

Fig. 7. Oscillating state: Re = 6000 , Pr = 17 , micro gravity conditions
a to f : streamline evolution versus time

These results were extended to a fully 3D case. The numerical results (Fig. 8) are in agreement with those obtained experimentally.

a) b)

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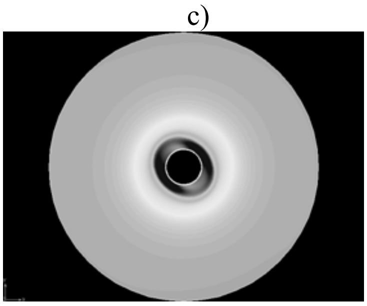 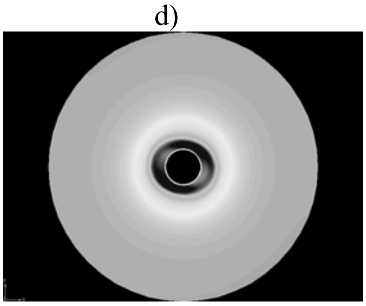

e) f)

Fig. 8. Oscillating state. Temperature field evolution versus time

B. VAPOUR BUBBLE (with phase change)

1. TEST CHAMBER

A test chamber has been performed for the boiling experiment with a single bubble in order to study during the single bubble growth (from its ignition to its detachment): - 1/ the flow around the bubble interface (thermocapillary vortex, the thermocapillary state) - 2/ the temperature field around the bubble and on the heated wall – 3/ the heat transfers between the heated wall and the bubble – 4/ the influence of the size of the heater.

The test chamber performed for the boiling experiment has been tested with a first liquid : water. On the one hand, because of a short-circuit of the heating the boiling experiment has not participated to the second parabolic flight campaign. This chamber allows us to establish a sufficient superheated wall at low pressure**.** Moreover in order to work with various liquids in closed circuit, a condenser has been realised with Peltier elements, radiators, and ventilators; The liquid tested is FC72 Fluorinert, because the saturation temperature is lower than the water one (Tsat = 56 °C for P = 1 atm). In this cell the heating face of the element is downward. We have chosen this new thermal configuration in order to perform works during parabolic flight campaign. In this case the temperature distribution is stayed stable during the increased gravity period. Moreover with this configuration, the gas bubble will not detach during the increased gravity period.

The aim of this test campaign is to perform – 1/ a heater in order to study boiling around a single bubble growing under a downfacing heater element. – 2/ a transparent heater element in order to observe the surface of the growing bubble and to study the dry surface, the contact line… .

2. EXPERIMENTAL RESULTS

Owing to the vaporization the bubble size increases and finally the bubble is detached from the wall (a film illustrates this behaviour). Figure 9 shows the time evolution of the radius of the bubble for three values of the subcooling shows the growth of a vapour bubble under the heating surface from its ignition to its detachment for a subcooling level ΔT = 15 K and a power P=1.45 W). In the three cases an oscillatory mode succeeds in a stable state starting from a breaking value of value of the radius of the bubble. Figure 10 shows the diagram of stability (bubble radius-Rb, subcooling-ΔT) between the stable mode and the oscillatory mode.

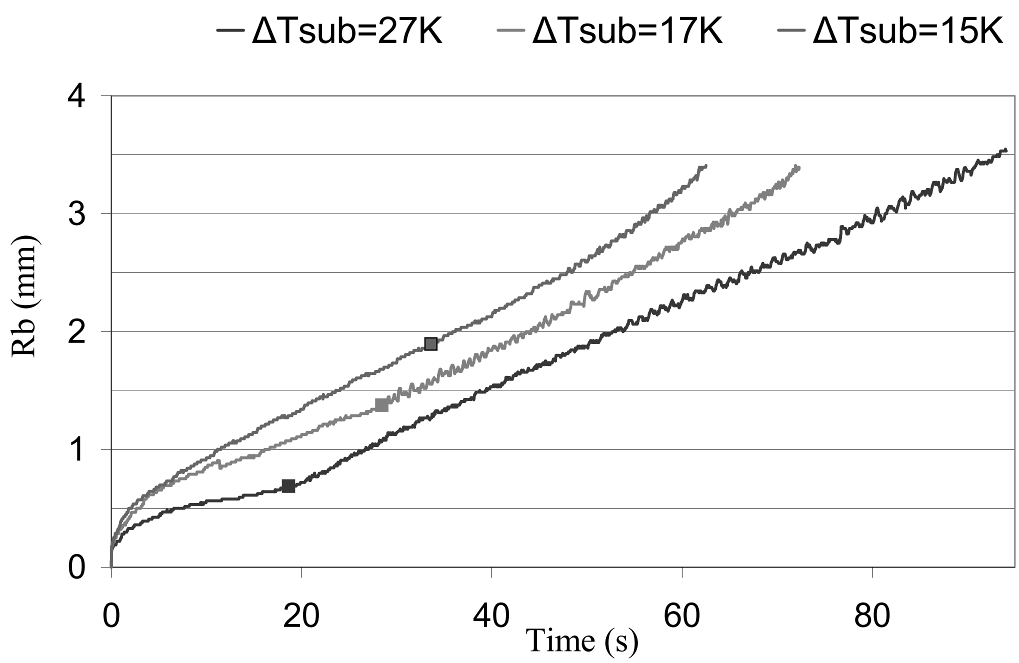

Fig. 9. Radius of the bubble versus time and critical value for the transition stable oscillating regime

The critical value is shown by a square

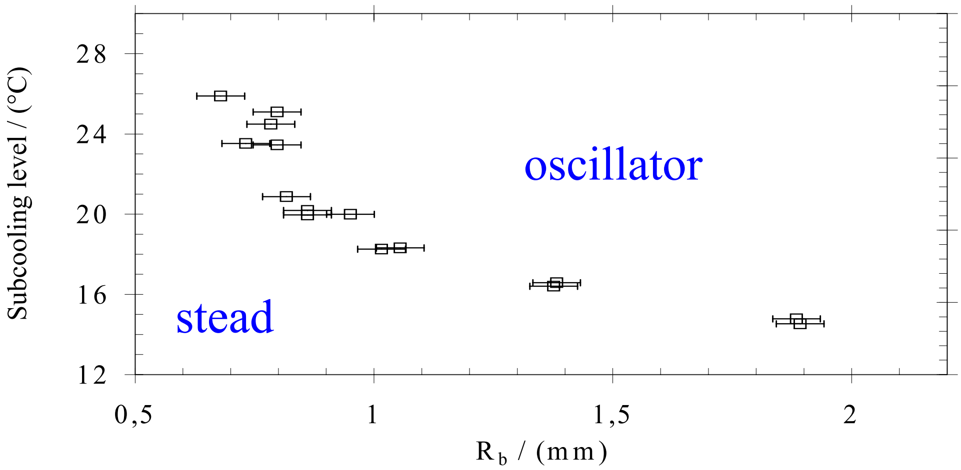

Fig. 10. Diagram (subcooling – ΔT, bubble radius – Rb) between the stable mode and the oscillatory mode

CONCLUSION

This study made it possible to show that the convective phenomena induced by the Marangoni effect around a bubble play a significant role in the heat transfer. The convection around the bubble can take a stable or oscillatory aspect, whether it is on the ground or in microgravity. The few results presented in this paper represent only a small part of a vaster study on boiling on the ground and in microgravity.

The influence of the Marangoni effect on the heat transfer around a air bubble on the ground and in microgravity. This transfer is enhanced in microgravity. Similar experiments are carried out on a growing vapour bubble. Characteristics of the threshold between stable and oscillating states are given. Results obtained from a numerical study performed with a method of finite elements are in agreement with experimental results.

Table 1. Thermophysical properties of the two kinds of silicone oil at 25°C

Density in kg/m3	Conductivity in W/(mK)	Kinematic viscosity in m^2/s	Specific heat in J/(kgK)	Temperature coefficient of surface tension in N/(mK)
816	0.1	1.10^{-6}	2050	$-8.24\ 10^{-5}$
950	0.14	20.10^{-6}	1630	$-6.23\ 10^{-5}$

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