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Quench cooling under reduced gravity

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We report quench cooling experiments performed with liquid O₂ under different levels of gravity as provided by a magnetic gravity compensation setup. A copper disk is quenched from 270K to 90K. It is found that when gravity is zero, the cooling time is abnormally long in comparison with any other gravity level. This phenomenon can be explained by the insulation effect of the gas surrounding the disk. The liquid subcooling is shown to drastically improve the heat exchange, thus reducing the cooling time (about 20 times). The effect of subcooling on the heat transfer is analyzed at different gravity levels. It is shown that such type of experiments cannot be used for the analysis of the critical heat flux (CHF) of the boiling crisis. The minimum heat flux (MHF) of boiling is analyzed instead.

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I. INTRODUCTION

The rocket engines for spatial applications need to be able to restart under low gravity conditions to place satellites on different orbits. The solid fuel engines are currently used for this purpose. The cryogenic fuel like hydrogen and oxygen is however much more advantageous energetically and is currently under study for next generations of the rocket engines. There is however an important limitation. After some period of inactivity, the temperature of the fuel injectors of such engines may rise above the temperatures at which the fuel may be in the liquid state because of the solar radiation. The engine cannot function before the injectors are not chilled down. The injectors are usually cooled by putting them into the contact with the cryogenic fluids (i.e. with the fuel), i.e. by the quench cooling. One thus needs to master the cooling time as a function of different parameters. The understanding of the latter phenomenon under reduced gravity conditions thus becomes important. In the present article we study the quenching of a hot metal piece in cryogenic fluids as a function of several parameters like the gravity level.

The prediction of cooling time necessitates the knowledge of the heat transfer coefficient which depends on temperature. To measure the influence of the gravity level on the value of the heat transfer coefficient, we have performed experiments in a liquid oxygen-filled cell. A copper disc was quickly immersed into this bath and cooled down (quenching method). The Earth gravity was compensated by the magnetic force in the OLGA (Oxygen Low Gravity Apparatus) facility located at CEA/Grenoble in France.

The objective of this article is three-fold. We aim to show that (i) one cannot measure the critical heat flux

of the boiling crisis in a quenching experiment and (ii) the subcooling improves greatly the cooling efficiency in microgravity that is otherwise very poor. Finally, we measure the dependence of the minimum flux of boiling (i. e. the threshold of the departure from film to nucleate boiling) as a function of gravity.

A. The quench cooling

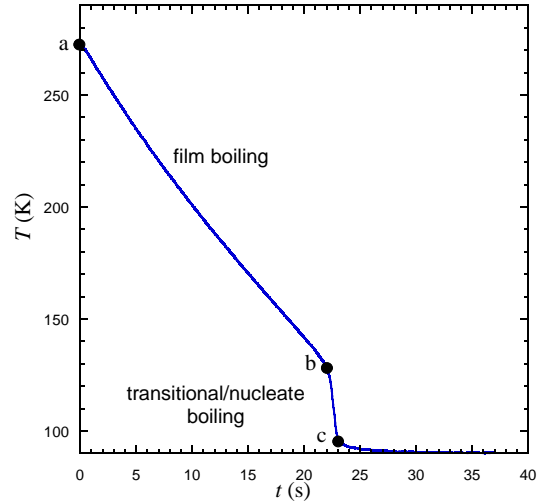


FIG. 1. Temperature evolution of a copper disk initially at about 270K dipped into O₂ bath at 90K under Earth gravity.

Consider what happens when a hot sample is dipped into a liquid. Fig. 1 presents a typical temperature evolution of a copper disk initially at about 270K dipped into a liquid O₂ bath at 90K under Earth gravity.

At a first stage (a-b zone), the temperature decreases slowly because the solid surface is completely covered by a layer of vapor which insulates the solid from the liquid. This is the film boiling regime, during which the

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vapor bubbles are generated at the vapor-liquid boundary. When the surface temperature becomes low enough, the liquid may come into direct contact with the sample and the bubbles start nucleating directly at the solid surface. This signifies the beginning of the nucleate boiling regime which provides much more efficient heat transfer and the temperature decreases very quickly (b-c zone). At the final stage, the solid temperature is not any more sufficiently high to induce boiling; the solid temperature approaches that of the liquid O₂ bath due to convection. The evolution of heat transfer regimes can be traced on the Nukiyama diagram (Fig. 2) presenting the heat flux q from the heater as a function of the sample temperature T . The system evolves from the right (film boiling regime) to the left in Fig. 2. The moment where the direct solid-liquid contact begins to occur corresponds to the minimum heat flux (MHF). From this moment, the transition from film to nucleate boiling starts. The line along which the system evolves depends on the thermal inertia of solid. If it was vanishingly small, a transition to the nucleate boiling regime would occur instantaneously (leftwise directed arrow in Fig. 2). In reality, a finite time is necessary to cool down the solid and the system evolves along the dotted curve. The heat flux attains a maximum value at a point where no part of the solid is covered by the persisting vapor film. The nucleate boiling regime occurs from that moment on. It is very important to distinguish the quenching curve from the boiling (solid) curve.

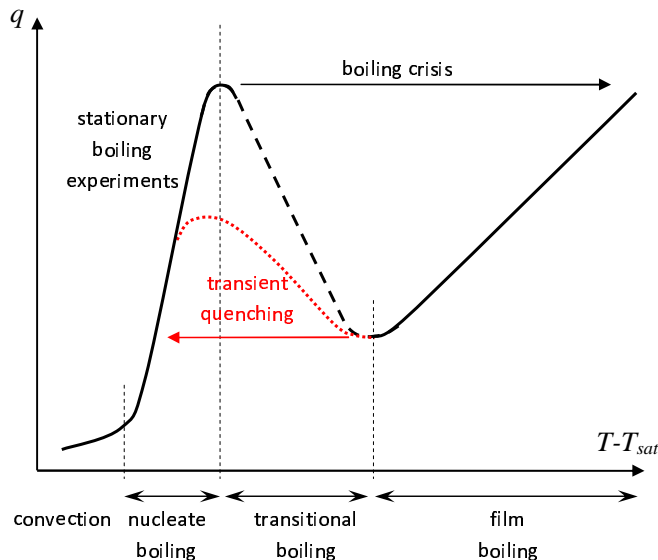


FIG. 2. (Color online) Schematic heat transfer curves for stationary boiling experiments and transient quenching.

The maximum heat flux (called critical heat flux, CHF) can only be recovered in the stationary boiling experiments (see, e.g. [1]) performed at fixed heat flux during each experiment. Till 1960s, the quenching experiments were considered to be suitable for the CHF determination [2, 3]. With the development of the quenching stud-

ies for the metallurgy (steel quenching), it became clear that only MHF may be obtained by this method [4], the maximum flux value depending strongly on the sample thermal inertia. The actual CHF may only be obtained for the samples of the large enough thermal inertia. However the CHF may hardly be studied in that case, which is evident from the following consideration.

During the cooling, the heat Q transferred from the sample to the liquid bath during the time Δt may be expressed as

$$Q = mC_P(T)(T(t) - T(t + \Delta t)), \quad (1)$$

where m is the mass of the disk, T its temperature, and t is the time. The specific heat of copper C_P depends on T ,

$$C_p(T) = -1.355 \times 10^{-7}T^4 + 1.303 \times 10^{-4}T^3 - 4.798 \times 10^{-2}T^2 + 8.331T - 217.964$$

The transferred heat may also be expressed with the heat transfer coefficient h ,

$$Q = hS(T - T_L)\Delta t, \quad (2)$$

where S is the total surface of the sample and T_L is the temperature of the liquid bath. By equating these expressions, one finds

$$h = \frac{mC_P[T(t)][T(t) - T(t + \Delta t)]}{S\Delta t[T(t) - T_L]}$$

and the heat flux $q = Q/(S\Delta t)$.

This method of measurements is valid only if the temperature of the sample is uniform during the cooling. For this, the Biot number

$$Bi = \frac{hL_c}{\lambda}$$

must be lower than 0.1 [5]. Here L_c is the characteristic length (a half thickness of the disk); λ is the copper thermal conductivity. It has been checked that the criterion $Bi < 0.1$ holds for all described experiments.

One can see now that the requirements of small $Bi < 0.1$ and large thermal inertia of the sample are contradictory. This explains why the quench method is hardly suitable for the CHF study. The objective of this article is the analysis of the MHF rather than of CHF. Besides we study the cooling dynamics and the impact of sub-cooling on it at various gravity levels.

II. EXPERIMENTAL APPARATUS

Experiments were performed in the OLGA facility (Fig.3). It is equipped with a superconductive coil and creates a magnetic force strong enough to compensate the buoyancy force in O₂.

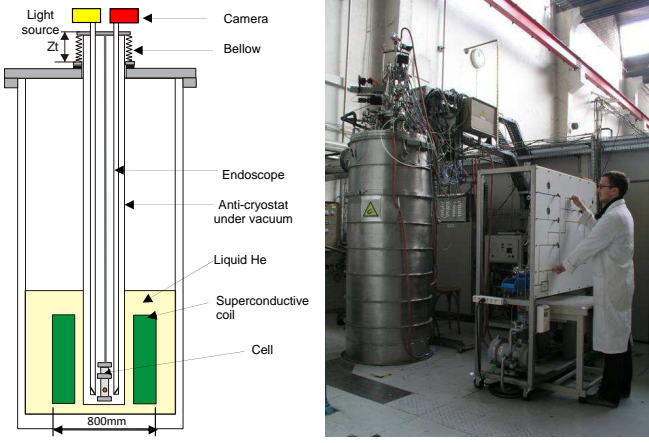


FIG. 3. (Color online) A sketch and a general view of the OLGA facility.

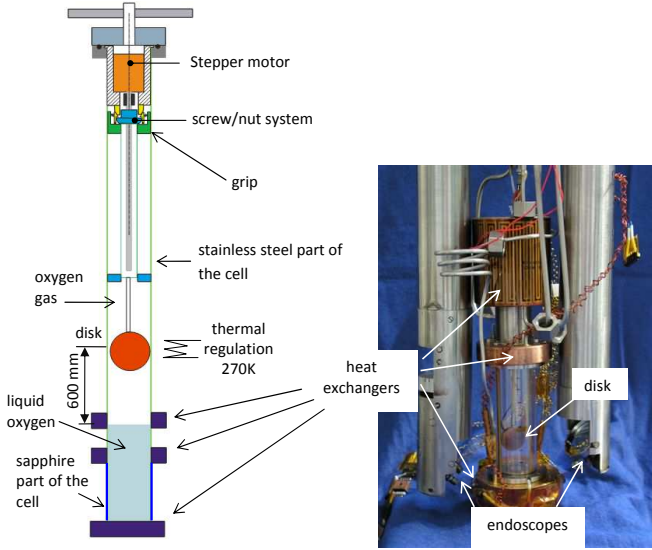


FIG. 4. (Color online) A sketch of the cell and a photo of its lower part (the upper part of the cell is removed). The disk is shown in the upper position on the sketch and in the lower on the photo.

Oxygen is contained in the experimental cell (Fig.4) placed in an anti-cryostat inserted into the 300 mm bore of the superconductive coil. Two endoscopes are used for observation: one for the light and another for the camera.

The lower part of the experimental cell is made of a sapphire tube of 30 mm diameter and 100 mm length closed by two copper flanges equipped with heat exchangers, inside which the gaseous cold helium may flow. The temperature of the two flanges is controlled within 0.01K with heaters. The upper part of the cell is the stainless steel tube. The pressure in the cell is measured with an accuracy of 10 mb. Liquid oxygen is obtained by condensing pure O₂ gas (99.995%) in the cell. The cell is brought to the desired temperature by regulating the power of heaters and helium flow rate in the heat ex-

changers that are situated at the top and at the bottom of the transparent part of the cell.

The disk is made of pure copper. Its diameter is 20.02 mm and its thickness is 2.98 mm. The weight of the disk is 7.68 g, its surface in contact with liquid is $S = 8.07 \text{ cm}^2$ and its RMS roughness is $0.8 \text{ }\mu\text{m}$. A hole was drilled to introduce a platinum thermometer (supplier: Heinz Messtechnik, model W60-50, class A; diameter 1.8 mm, length 11 mm) in its heart. After each quench experiment, the disk may be risen into a hot zone that situates 0.6 m above the transparent part of the cell with a screw/nut system driven by a stepper motor. The hot zone of the cell is regulated at 270 K. Once the disk attains this temperature, the grip is loosened again and the disk drops into the liquid. Meanwhile, the disk temperature is acquired at a frequency of 100 Hz.

III. GRAVITY COMPENSATION

The principle of magnetic compensation of gravity in a pure non-magnetic substance is an application of the magnetic volume force opposite to the Earth gravity [6–8].

This force per unit volume is given by the expression

$$\vec{F}_m = \frac{\chi_m}{2\mu_0} \nabla(B^2), \quad (3)$$

where B is the magnetic field, μ_0 is the magnetic permeability of vacuum and χ_m the magnetic susceptibility of the material.

Since χ_m is proportional to the density ρ of the non-magnetic substance, one may introduce a quantity $\alpha = \chi_m/\rho$ independent of the density. It means that the buoyancy force is compensated if one applies the field with $dB^2/dz = 2\mu_0 g/\alpha$, where g is the Earth gravity acceleration and z is the vertical coordinate. For O₂ at 90K, $2\mu_0 g/\alpha \sim 8 \text{ T}^2/\text{m}$. These conditions are achieved in OLGA facility near the bottom of the superconductive coil.

It was demonstrated [9] that the magnetic force (3) cannot be made constant in a volume. In our experimental cell, Earth gravity may be exactly compensated at a single point called complete compensation point. Such conditions are called hereafter $0g$ and the corresponding coil current is denoted I_{0g} . In the vicinity of this point, a residual acceleration acts on O₂ [10]. As the magnetic force is a way too small to compensate the gravity for copper, the disk falls with the Earth gravity acceleration. Its stop point situates at $z = -242 \text{ mm}$ with respect to the center of the coil. At this location, Fig. 5 gives the calculated iso-values of residual gravity acceleration modulus at $0g$ conditions. One can see that at the edge of the disk, the residual acceleration is smaller than 2% of g .

To achieve $0g$ at the required place inside the cell, a single bubble is generated by the boiling process with a heater situated at the bottom of the cell. Then the current in the coil is adjusted until the bubble center

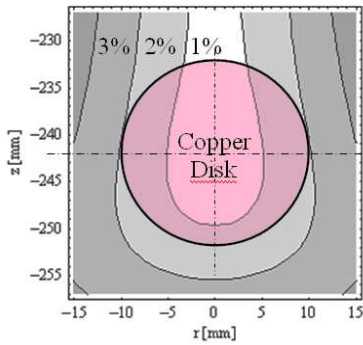


FIG. 5. (Color online) Iso lines of the residual acceleration modulus in % of g inside the cell of OLGA at the ending point of the disk fall at $0g$.

coincides with the optimal previously calculated point (Fig. 6).

The effective gravity level [8] may be varied by changing the coil current I . It is known [11] that the effective gravity level g^* at the geometrical point of complete compensation is given by the equation

$$g^* = \left(1 - \frac{I^2}{I_{0g}^2}\right) g.$$

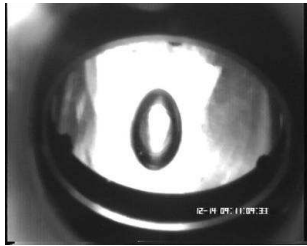


FIG. 6. Image of O_2 bubble at $0g$ inside the cell at equilibrium as seen in the periscope mirror used to adjust the position of the exact compensation point with respect to the cell. For this case, the temperature is $92.24K$ and the current in the coil is $I_{0g} = 241$ A. The elongated shape of the bubble is due to the weak coupling of the magnetic field with the gas-liquid interface shape [8].

The magnetic susceptibility of oxygen varies with temperature, and I_{0g} depends weakly on the liquid temperature. For the isothermal conditions, the currents for the complete gravity compensation are $I_{0g} = 239.7$ A at $90.07K$ (pressure of 1 bar, at saturation) and $I_{0g} = 241$ A at $92.24K$ (subcooling 5K for the pressure of 2 bars). When the disk is dropped into liquid O_2 , the liquid is slightly heated up, resulting in a small decrease of the magnetic susceptibility. By observing the movement of the gas generated by boiling around the disk (Fig. 7), we could see that the current had to be slightly increased to obtain $0g$ in the cell during the disk cooling. In this case, $I_{0g} = 242.1$ A at $90.07K$, and $I_{0g} = 245.18$ A at $92.24K$.

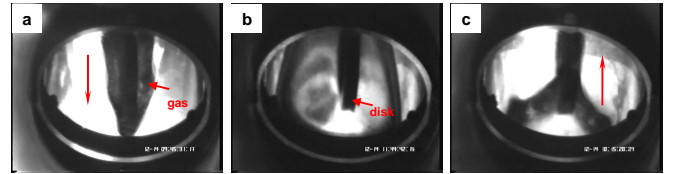


FIG. 7. (Color online) Film boiling at different gravity (its direction is shown with vertical arrows) at initial liquid O_2 temperature (before disk drop) $92.24K$. a) $I = 241$ A: the residual gravity is directed downwards and the gas surrounding the disk slowly rises. b) $I = 245.18$ A: the gas recondenses without rising and surrounds the disk during all the cooling time (zero gravity). c) $I = 252.7$ A: the residual gravity is directed upwards and the gas goes downwards.

IV. EXPERIMENTAL RESULTS

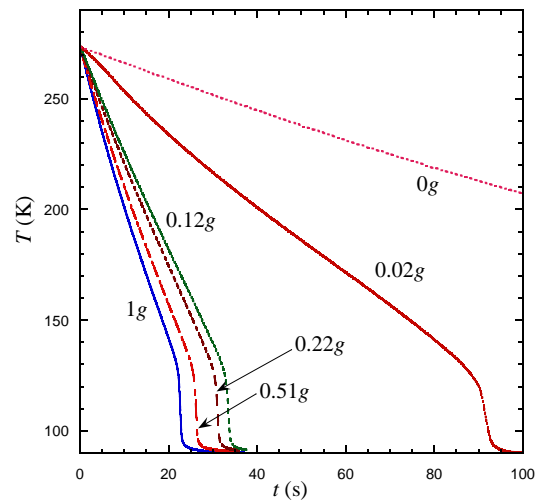


FIG. 8. (Color online) Evolution of the copper disk temperature dipped into O_2 bath at different gravity levels for the saturated case.

Quenching experiments were performed for two O_2 thermodynamic conditions: saturated O_2 and subcooled O_2 with respect to its saturation temperature for given pressure that was controlled independently since the cell was connected to a large oxygen-filled vessel.

A. Case of saturated liquid

For saturated O_2 experiments, the temperature of the cell was regulated at $90.07K$ and the vessel pressure was maintained at 1 bar (which is the saturation pressure corresponding to this temperature). 15 quenches were performed.

1. Cooling curves of the disk

Fig. 8 shows the cooling curves of the disk for different levels of gravity. We can see that the lower the gravity, the larger is the cooling time. The $0g$ cooling time is very large with respect to other cases and the corresponding curve is truncated: it took more than 10 minutes to cool down the disk. The complete curve is shown in the inset to Fig. 13 below.

2. Heat transfer curves

Using the above described method, we have calculated the heat transfer curves for different levels of gravity (Fig. 9). The film boiling points were calculated by making a centered moving average on 50 points for the film boiling and from 10 to 20 points for the transitional/nucleate boiling. One can clearly see the influence of the gravity level on the transferred heat flux in film boiling regime and on the maximum and minimum heat flux values.

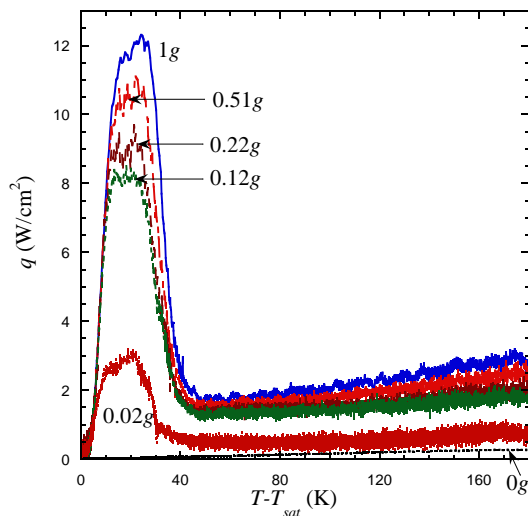


FIG. 9. (Color online) Heat transfer curves for saturated O_2 quench cooling at 1 bar and different gravity levels.

Fig. 10 is a comparison of Kutateladze and Breen & Westwater correlations [12] with our experiment under $1g$. One can see that the quench method gives the maximal heat flux $\sim 12 \text{ W/cm}^2$, which is two times lower than the CHF value 24.9 W/cm^2 obtained with the Kutateladze correlation. The latter value reasonably agrees with the experimental value ($22\text{--}23 \text{ W/cm}^2$) obtained in pool boiling experiments [13]. The low value of the maximum heat flux reflects the transient nature of the quench cooling as discussed in Fig. 2(sec. I A).

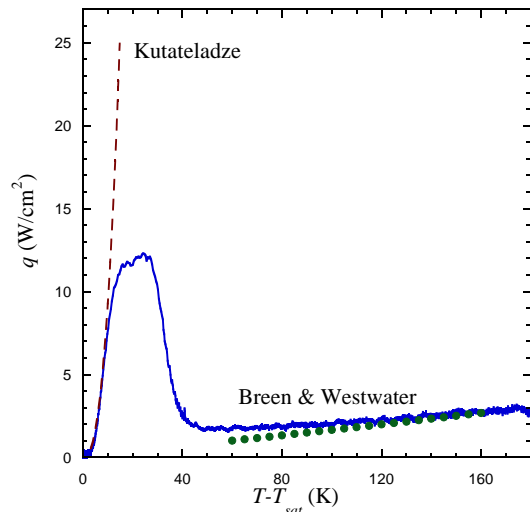


FIG. 10. (Color online) Comparison of the Kutateladze (broken line) and Breen & Westwater (circles) correlations with our data from Fig. 9 corresponding to $1g$ (solid line).

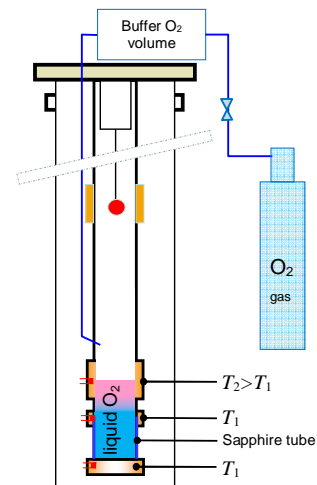


FIG. 11. (Color online) Sketch showing the principle used for subcooling experiments.

B. Case of subcooled liquid

To measure the subcooling influence, experiments were performed for several subcooling values. The subcooling was obtained with the following method (cf. Fig. 11). The temperatures of two lower heat exchangers of the cell (cf. Fig. 4) are regulated at the same value T_1 . The temperature T_2 of the upper heat exchanger is regulated at a higher value equal to the saturation temperature corresponding to the gas pressure. Under these conditions, the equilibrium level of liquid forms in the region of cell maintained at the temperature T_2 . A thermal gradient exists in the liquid between two upper heat exchangers. The liquid is isothermal at T_1 in between two lower heat exchanges. The final drop point of disk is

situated in this initially isothermal region.

To achieve the 5K subcooling, $T_1 = 92.24\text{K}$ and $T_2 = 97.24\text{K}$. The latter temperature corresponds to the pressure of 2 bars. For the 7K subcooling (see below), $T_1 = 90.24\text{K}$.

1. Cooling curves

Fig. 12 shows the raw cooling curves of the disk for 6 levels of gravity. The temperature of cell was regulated at 92.24K and the pressure was adjusted at 2 bars which results in a subcooling of 5K. The temperature acquisition frequency was 100 Hz. Similarly to the saturated case, the lower the gravity level, the longer is the cooling time. Unlike the saturated case, the $0g$ cooling time is only twice larger than that of the $1g$ case.

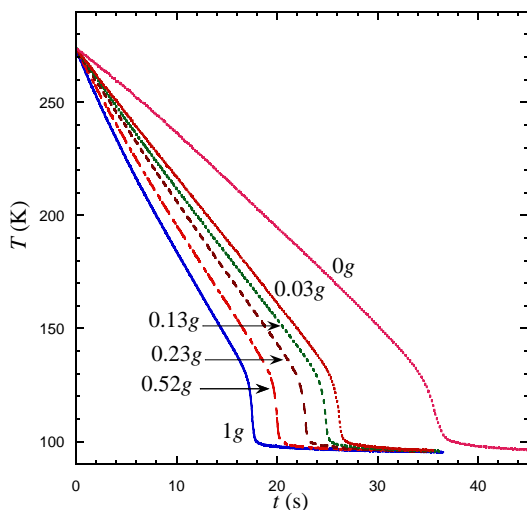


FIG. 12. (Color online) Evolution of the disk temperature at different gravity levels for the 5K subcooled case.

2. Impact of subcooling

Fig. 13 shows that the subcooling reduces drastically (20 times) the general cooling time at $0g$ while the effect at any nonzero gravity is much weaker (cf. Figs. 8 and 12). Such a reduction may be explained as follows. Fig. 7b shows the formation at $0g$ of a vapor bubble that surrounds the solid and completely insulates it from the liquid. The bubble can recondense if the liquid is subcooled and cannot recondense if the liquid is saturated. For the saturated case, the heat exchange is thus produced via the weak heat conduction through the vapor and through the almost non-conductive at cryogenic temperatures stainless steel rod that supports the disk (cf. Fig. 4). When the liquid is subcooled, the recondensation of the vapor at the external bubble interface is very efficient and the gas layer surrounding the disk is much

thinner. This effect improves the heat exchange thus favoring cooling.

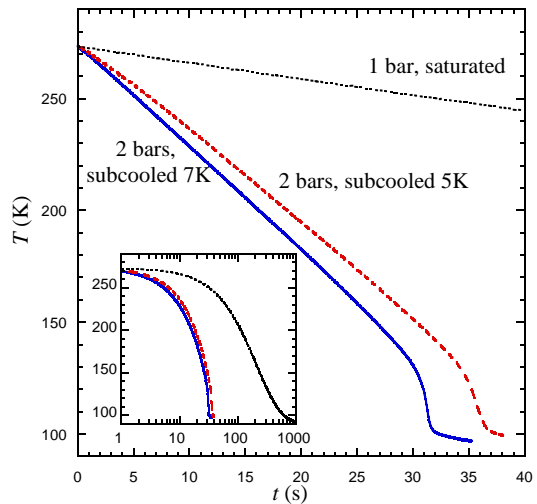


FIG. 13. (Color online) Evolution of the disk temperature at different subcooling levels at $0g$. The same curves are shown in the inset in the semi logarithmic scale.

3. Heat transfer curves

We have plotted the heat transfer curves for 6 levels of gravity (Fig. 14) using the same method as the one used for the saturated case. One can see that unlike the saturated quench, the maximum and the minimum heat flux values are both nonzero for the $0g$ case.

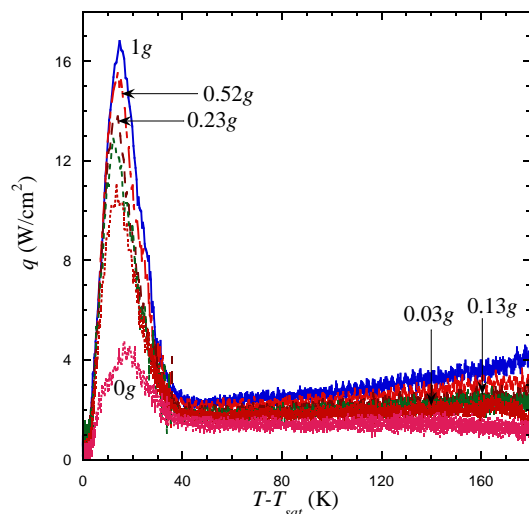


FIG. 14. (Color online) Heat transfer curves for the 5K subcooling case at different gravity levels.

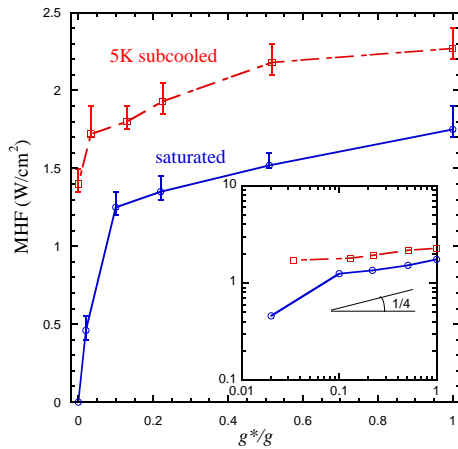


FIG. 15. (Color online) Minimum heat flux versus gravity level for saturated and subcooled O_2 . Inset: same in log-log scale; the $1/4$ slope is shown for comparison.

C. Minimum heat flux

Fig. 15 shows the minimum heat flux as a function of the gravity level. The minimum value was obtained by fitting the raw data with a second degree polynomial. The MHF occurrence is usually associated with the Taylor instability of the vapor film [14, 15] so that $q_{MHF} \sim g^{1/4}$ should be satisfied. Fig. 15 shows an exponent close to this value.

V. CONCLUSION

Quench cooling has been analyzed under different gravity levels. Earth gravity was compensated with magnetic forces. Measurements were performed by quenching a copper disk of 20 mm diameter and 3 mm thickness from 270K to 90K. The analysis of different boiling regimes has shown that the study of the critical heat flux (CHF) via quenching experiments is hardly possible because of the transient nature of the quench cooling: the maximum heat flux value is twice smaller than the CHF measured by other authors in the stationary boiling experiments.

It has been shown that cooling via quenching in microgravity takes usually exceedingly long time because the vapor generated during the boiling envelopes completely the cooled body (film boiling regime), thus thermally insulating it from the liquid. It is shown that the artificial subcooling (for instance, by transient pressurization) can drastically accelerate the cooling. This speeding up is explained by the recondensation of the vapor envelope at the vapor-liquid interface in case of subcooling.

The dependence of the heat transfer and, in particular, of the minimum heat flux of boiling (MHF) on gravity is analyzed. As expected, the heat transfer improves with the gravity level. The MHF gravity dependence shows an exponent close to that of the Zuber theory (exponent $1/4$).

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