CONFINED AND UNCONFINED NUCLEATE BOILING UNDER TERRESTRIAL AND MICROGRAVITY CONDITIONS

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Abstract. *This paper presents experimental results for subcooled nucleated boiling of n-Pentane on a heating surface facing downward, for two different degrees of confinement, s = 0.3 and s = 0.9mm and for low and moderate heat fluxes (lower than 60 kW/m^2). The microgravity conditions were obtained from the Maracati II space mission, which involved the launching of the suborbital Brazilian rocket VSB 30. The results under terrestrial conditions showed a decrease in the heat transfer coefficient with an increase in the confinement. It was observed that the heat transfer coefficient increases with an increase in the liquid temperature inside the boiling chamber. The results under microgravity conditions were compared with those for terrestrial conditions. For the confined case, the experimental data had the same trend. However, for the unconfined case, according to a preliminary analysis, there was a difference between the data obtained under microgravity and terrestrial gravity conditions.*

Keywords*: Boiling, Nucleate boiling, Microgravity, Bond number, Heat transfer*

1. INTRODUCTION

Space exploration requires the development of compact and lightweight devices equipped with microprocessors whose temperature must be controlled to ensure their operation. One way to dissipate the high heat fluxes of these microprocessors is through devices whose operating principle is based on phase-change processes, such as boiling and condensation.

The study of the heat transfer in nucleate boiling has been investigated by various researchers, for example, Yao and Chang (1983), Nishikawa *et al*. (1984), Bonjour and Lallemand (1998), Kim *et al*. (2005) who studied the nucleate boiling on inclined, vertical and horizontal surfaces. The characteristic most commonly observed in the results of previous studies is that the heat transfer coefficient increases when the distance between the heated and unheated surfaces decreases (the confinement increases) for moderate heat fluxes (Passos *et al*., 2004, Passos *et al*. 2005a and Cardoso *et al*., 2011). For relatively high heat fluxes, this enhancement effect disappears and the heat transfer coefficient decreases with increasing confinement and the dryout heat flux (DHF) can be attained as shown by Katto *et al*. (1977).

The effect of the confinement on the bubbles can be characterized by a dimensionless parameter known as the Bond number, *Bo*, defined as the ratio of the characteristic length to the confined space, *s*, and the capillary length, *L.* The latter is proportional to the detachment diameter of the vapor bubble in a pool and defined as Eq.1 (Carey, 1992):

$$L = \sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}} \quad (1)$$

where σ, g, ρ_l and ρ_v represent the surface tension, the acceleration due to gravity, the liquid density and the vapor density, respectively. Thus, the Bond number $Bo = s/L$. In general, when $Bo < 1$ the effect of the confinement is important and the bubbles tend to be coalesced and deformed, while for $Bo > 1$, the bubbles become isolated (Ishibashi and Nishikawa, 1969).

The increase in the heat transfer coefficient when $Bo < 1$ is explained by the evaporation of a thin liquid film, which is present between the heated surface and the base of the deformed bubble (Ishibashi and Nishikawa, 1969 and Katto *et al*., 1977).

Passos *et al*. (2004) showed the effect of confinement on the partial boiling curve, for FC72 and saturated temperature, with different degrees of confinement (*s* = 0.2, 0.5, 1.0 and 13 mm). For *s* = 0.2 and 0.5 mm and for heat fluxes between 5 and 22 kW/m^2, the superheating value was lower when compared with the case where s = 13 mm, showing an increase in the heat transfer coefficient. Passos *et al*. (2005b) reported results for the confined and unconfined nucleate boiling, for FC72 and FC87, at atmospheric pressure and for low and moderate heat fluxes (less than 45 kW/m^2), on a heating surface facing downward. The experimental data showed an increase in the heat transfer coefficient for *s* = 0.2 and 0.5 mm, and a higher heat transfer coefficient for FC72.

Cardoso *et al*. (2009) experimentally studied saturated nucleate boiling of n-Pentane on a heating surface facing upward for two different degrees of confinement (s = 0.2; 13 mm). The authors analyzed the partial boiling curves and they observed an effect of the confinement only for s = 0.2 mm and also that the heat transfer coefficient increased when the confinement increased (decrease in the gap).

According to Carey (1992), for subcooled nucleate boiling and for the unconfined case, the subcooling has no clear effect on the heat transfer and we can use the correlations for saturated boiling. A study on the subcooling effect was performed by Passos and Reinaldo (2000), where the authors obtained the partial boiling curves for different fluid temperatures and for smooth and grooved vertical tubes.

The effect of subcooling on confined nucleate boiling was studied by Passos *et al*. (2004) on a heating surface facing downward, at atmospheric pressure using FC72. These researchers analyzed two different subcooling values, ΔT_{sub} = 26.6 °C corresponding to a liquid temperature of 30 °C and ΔT_{sub} = 46.6 °C corresponding to a liquid temperature of 10 °C. They reported an increase in the heat transfer coefficient with an increase in the subcooling. Su *et al*. (2008) used water, at atmospheric pressure, as the working fluid and studied the effect of subcooling on a stainless steel surface, for different degrees of confinement. According to these authors, when the boiling phenomenon occurs on a surface facing downward in a confined space, the natural movement of the micro-region does not occur, causing a reduction in the heat transfer coefficient. Marek and Straub (2001) explained that a larger amount of non-condensable gas is carried with the vapor and it accumulates on the upper part of the vapor bubble, the vapor condensation region. The gas causes a significant reduction in the temperature in this region and the rate of heat transfer is reduced.

Straub *et al*. (1990), Oka *et al*. (1995) and Shatto *et al*. (1996) showed that under reduced gravity the vapor bubbles on the heating surface are larger than those formed under Earth's gravity. Snyder and Chung (2000) show images obtained under terrestrial gravity and also under microgravity.

Kim *et al*. (2002) studied the subcooled nucleate boiling regime under reduced gravity, terrestrial gravity and high gravity, with FC72 and different subcooling values. They showed that the heat transfer coefficient is independent of the subcooling and gravity values. Kannengieser *et al*. (2009) analyzed the effects of the absence of gravity, for different pressure and subcooling conditions. The results showed that the heat transfer coefficient is influenced by the effects of pressure and subcooling only for low superheating values. However, this difference disappears when there is an increase in the superheating value and the pressure effect becomes more pronounced than the effect of subcooling.

Straub (2001) reported the results obtained on parabolic flights, for various heater types (flat plates, wires, circular heaters) and refrigerants (R11, R12, R113, R123, R134a), under saturated conditions and with subcooling. The most important results obtained by Straub *et al*. (2001) were: a) the increase or decrease in the heat transfer coefficient under microgravity is limited to ± 30 %; b) the heat transfer coefficient under microgravity always decreases with increasing heat flux; c) the subcooling has no influence on the heat transfer coefficient. Di Marco and Grassi (2002) performed experiments with FC72 and R113 on a platinum wire under subcooled conditions and on a parabolic flight and sounding rocket. They observed no notable effect on the heat transfer coefficient, although, the results for the critical heat flux (CHF) were 50 % lower than the results obtained under terrestrial gravity. Oka *et al*. (1995) studied the subcooled nucleate boiling of n-Pentane, CFC113 and water under reduced gravity (in the order of 10-2 g). They observed a reduction in the heat transfer for the nucleate boiling regime using water as the working fluid, however, for the refrigerants, the deterioration in the heat transfer coefficient due to the microgravity reduction was notable only for high heat fluxes. For these fluids, they noted a reduction of approximately 40 % in the CHF when compared with terrestrial results.

The principal goal of this study is to investigate the behavior of subcooled nucleate boiling and the influence of the initial fluid temperature on the partial boiling curve, for different degrees of confinement, under terrestrial gravity conditions. Comparative studies of experimental results obtained under microgravity and terrestrial gravity conditions, for confined and unconfined cases, were carried out.

2. EXPERIMENTAL SETUP

Figure 1 shows the schematic of the experimental apparatus developed to perform tests under terrestrial gravity and under microgravity. The experimental setup consists of a boiling chamber and a pressure transducer in the upper part and a photographic camera mounted on the support base. The boiling chamber consists of an aluminum cylindrical chamber filled with n-Pentane.

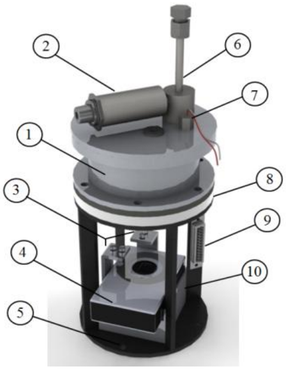

Figure 1. Scheme of the experimental apparatus: 1) boiling chamber; 2) pressure transducer; 3) LEDs; 4) camera; 5) support; 6) working fluid inlet; 7) thermistor; 8) acrylic base; 9) connector; 10) photographic camera support.

The test sections consist of a copper disc with a 12 mm diameter and 3 mm thickness, mounted onto the end of PVC tubes, with two different distances from the bottom of the boiling chamber, as shown in Fig. 2. Mounted in the lower part of the boiling chamber there is a transparent acrylic piece, allowing the visualization of the boiling phenomenon on the copper disc. The visualization was obtained with a Canon camera, model Power Shot SD1100 IS, 8.0 Megapixel, Lens 6.2-18.6 mm f/2.8-4.9. The pressure transducer, model PX302 Omega, measures the pressure inside the boiling chamber and is fixed laterally on the coupling used to charge and seal the working fluid.
The degree of confinement is a function of the distance between the copper disc and the acrylic base of the boiling chamber. The confinement distances of 0.3, 0.9, 10.4 and 11 mm were analyzed under terrestrial gravity and of s = 0.3 and 10.4 mm under microgravity. There are three thermistors of 10 Ω, set in the copper disc close to its center.

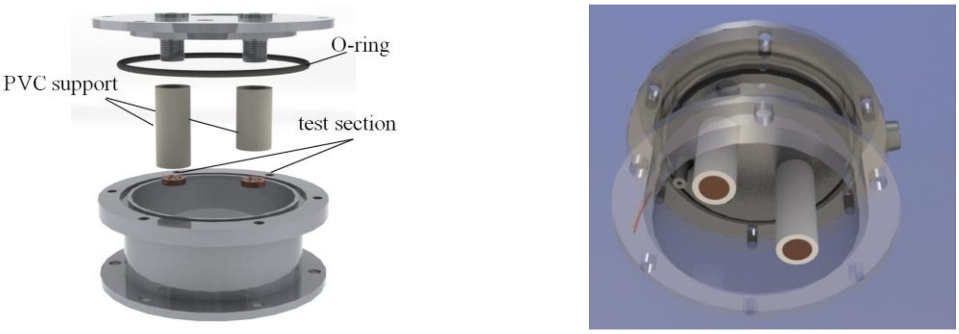

Figure 2. View of the inside of the boiling chamber.

The copper disc is heated by an 11 Ω electrical resistance skin heater fixed by epoxy resin to the upper side of the disc. A compact microprocessor, model Athena II PC/104 CPU, with VIA Mark 800 MHz and an integrated acquisition system (Diamond Systems), controls the power supplied by an program executable in C++.

The effect of the initial temperature of working fluid on the partial boiling curve was investigated. Therefore, the boiling chamber was surrounded by a silicone tube cooled by water whose temperature is controlled by a cryostat MQBMP-01 model. The boiling chamber has no relief valve or volume compensating dilatation of the fluid inside the chamber during the tests. The data acquisition system records five temperature and pressure measurements per second. The stability condition is reached in 60 seconds for the first heat flux value.

The experimental procedure was always the same in order to ensure the repeatability of the results. Heat fluxes of 20, 30, 40, 50 and 60 kW/m^2 were imposed, with intervals of 72 s for each flux and a total of 360 s for a complete test. The experimental uncertainty for the temperature was ± 0.7 °C, for the heat fluxes was 1.4 % to 2.2 %, and for the heat transfer coefficient was 1.9 % to 3.6 %.

For the tests performed under microgravity, the test information is stored in the electronic system and transmitted by telemetry. The activation of the experiment during the flight occurs approximately 1min after launch, when the rocket reaches microgravity. The microgravity period is approximately 390 seconds.

The experimental data under microgravity were obtained on a suborbital flight of the Brazilian rocket VSB-30, during Operation Maracati-II, which was launched from Alcântara Launch Center (CLA), Maranhão – Brazil. The microgravity environment achieved was less than 10^{-6} g. Figure 3 shows the variation in the gravity acceleration versus time for the VSB-30 rocket.

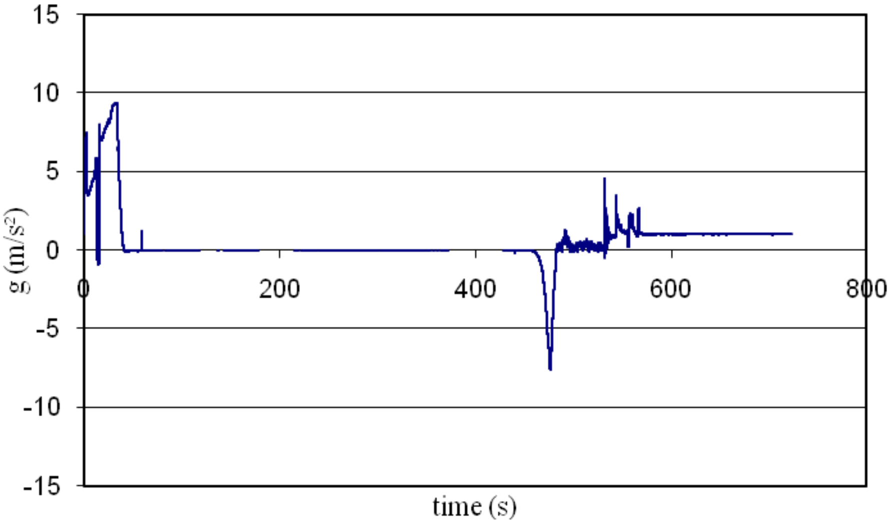

Figure 3. Evolution of gravity, during parabolic flight of the suborbital Brazilian rocket VSB 30.

3. RESULTS

3.1. Results under terrestrial gravity

In Fig. 4 the results for the heat transfer coefficient (W/m² K) as a function of the heat flux are shown for *s* = 0.3, 0.9, 10.4 and 11 mm with an n-Pentane temperature of 36 ºC.

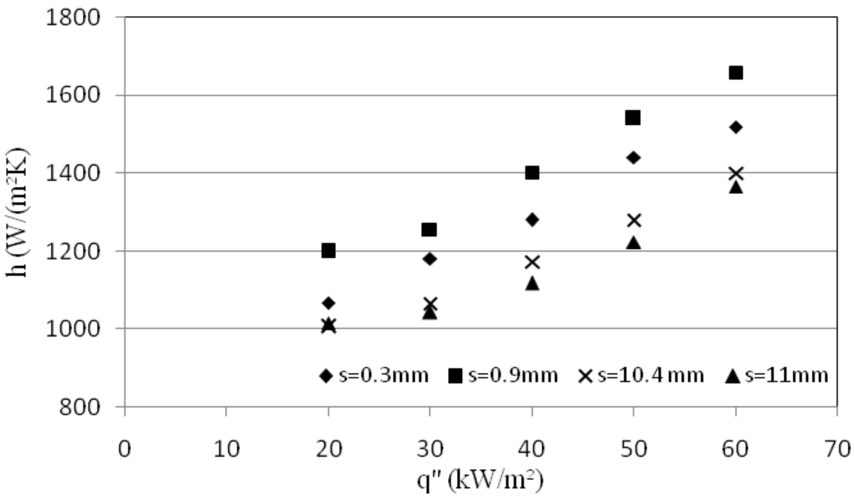

Figure 4. Effect of confinement on the heat transfer coefficient under terrestrial conditions.

For *s* = 0.3 and 0.9 mm there is a decrease in the heat transfer coefficient, *h*, when *s* decreases. This result is the opposed to that obtained for the saturated nucleate boiling regime, where an increase in the confinement (for low and moderated heat fluxes) causes an increase in the heat transfer coefficient. In saturated nucleate boiling, the contact area between the heated surface and the liquid located between the vapor bubble and the heated disk increases with increasing confinement, allowing an improvement in the heat transfer.

In the confined case, the limited space hinders the fluid movement. Without natural convection, the ideal situation occurs when there is microlayer vaporization and condensation at the other edge of the vapor bubble (in saturated boiling). In other words, the vapor bubble acts as a heat pump or heat pipe. The base of the bubble receives heat from the heated surface, acting as an evaporator, and the top of the vapor bubble plays the role of a condenser. For *s* = 0.9 mm, there is a balance between the evaporation and condensation rates. For *s* = 0.3 mm, condensation is hindered because the fluid temperature rises and due to vaporization, and the bubble continues to grow in volume. After a certain point, as the liquid flow rate for the region between the vapor bubble and the heated surface decreases, there is a drying process of the microlayer, causing a decrease in the heat transfer coefficient. For the subcooled confined nucleate boiling, this phenomenon does not occur because the liquid temperature outside the superheated liquid layer is equal to or close to the saturation temperature, which maintains the balance between the evaporation and condensation rates. For cases without confinement (s = 10.4 and 11 mm), the heat transfer is lower because the residence time and growth of vapor bubbles formed on the surface is reduced.

Figure 5 shows the partial boiling curve for the n-Pentane, for degrees of confinement of 0.3 and 0.9 mm with the heating surface facing downward. For s = 0.9 mm, the experimental points are shifted to the left, characterizing an enhancement in the heat transfer for the lesser degree of confinement.

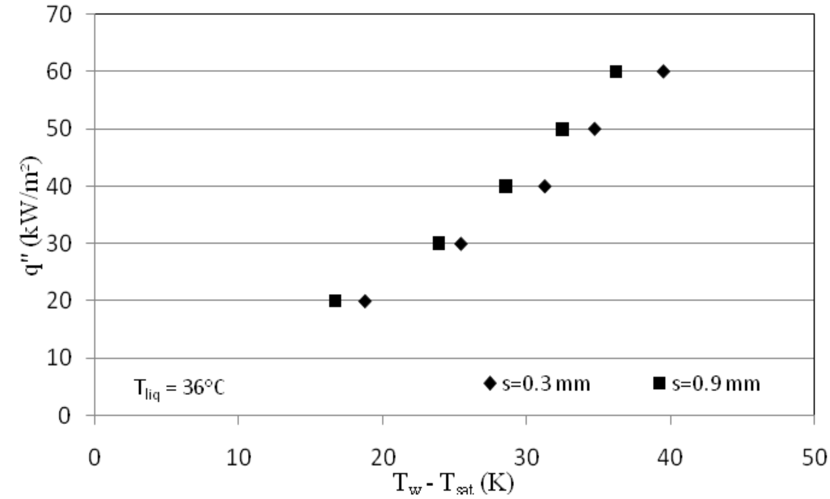

Figure 5. Effect of confinement on the partial boiling curve, for n-Pentane under terrestrial conditions.

In subcooled nucleate boiling case, when the confinement increases the condensation on top of the vapor bubble (in contact with the confined element) decreases, because the liquid temperature increases. When this occurs, the imbalance between the evaporation and condensation rates affects the heat transfer coefficient. For the confined saturated boiling regime, the heat transfer increases, as demonstrated in studies such as Katto (1977), Zhao *et al*. (2003), Cardoso *et al*. (2009) and Rops *et al*. (2009).

The effect of the initial liquid temperature on the partial boiling curve is shown in Fig. 6 for s = 0.9 mm and in Fig. 7 for s = 11.0 mm.

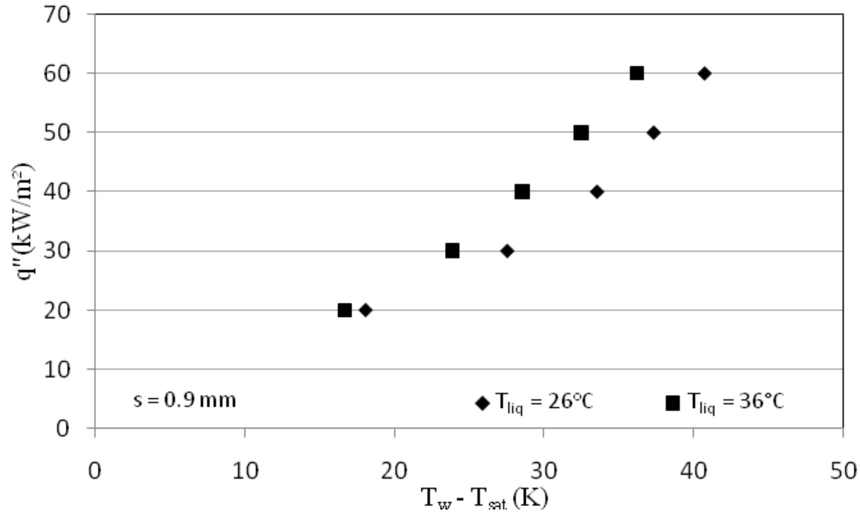

Figure 6. Effect of the liquid temperature on the partial boiling curve for s = 0.9mm under terrestrial conditions.

In Fig. 6, the heat transfer process is intensified for the case with higher liquid temperature. For heat fluxes higher than 40 kW/m², there is a difference of 5 °C in the heated surface temperature. For q = 20 and 30 kW/m², this difference is smaller, indicating that the vapor bubbles are small and cannot trap the liquid in the region between the base of the bubble and the heated surface. The pressure range was 1.14 to 1.18 bar for T_{liq} = 26 °C and 1.44 to 1.55 for T_{liq} = 36 °C.

In the case without confinement (s = 11.0 mm) shown in Fig. 7, the liquid temperature in contact with the heated surface, after the first heat flux (q = 20 kW/m²), is dependent only on the initial temperature of the liquid in the chamber. The pressure range was 1 to 1.15bar for T_{liq} = 23.7 °C and 1.45 to 1.54 for T_{liq} = 35.7 °C.

It is important to note that the same trend was observed for the effect of the liquid temperature on the heat transfer coefficient, regardless of the confinement degree.

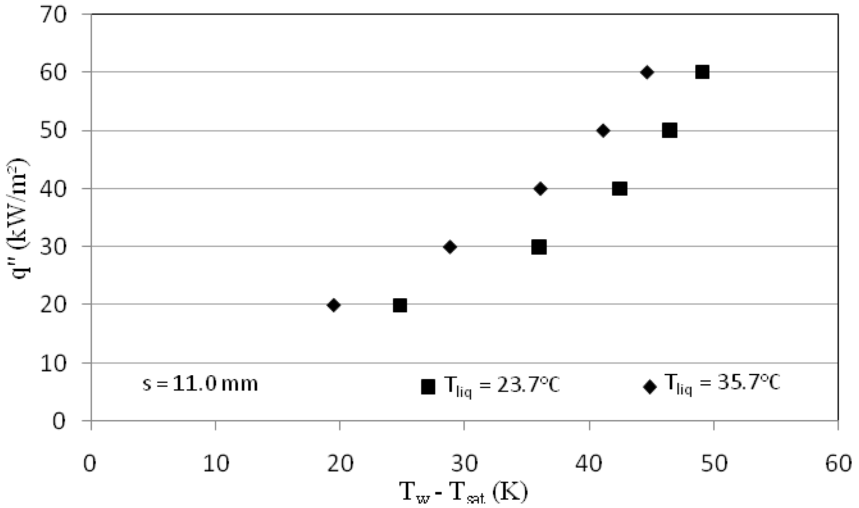

Figure 7. Effect of the liquid temperature, for *s* = 11 mm under terrestrial conditions.

Figure 8 shows the effect of the initial liquid temperature for the case without confinement, *s* = 10.4 mm. In this case, increasing the initial temperature increases the heat transfer coefficient, for the same heat flux. For higher heat fluxes (40 to 60 kW/m²) the nucleate boiling is intensified because the heated surface is facing downward.

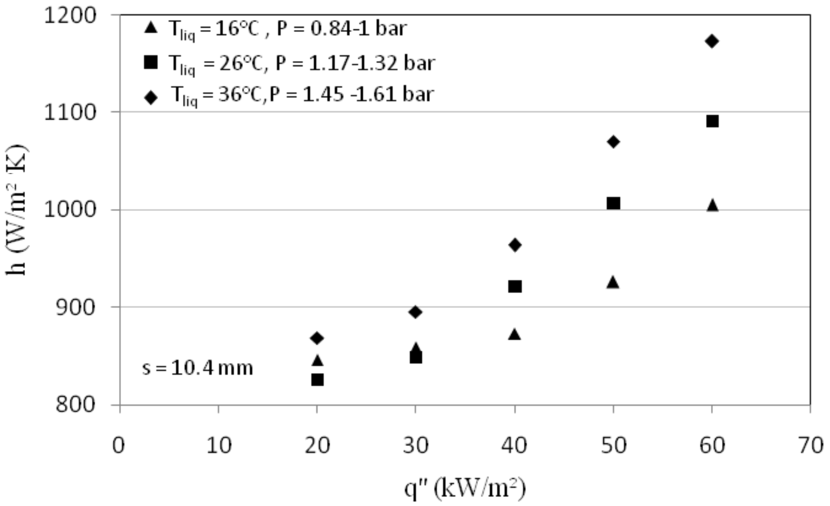

Figure 8. Effect of the liquid temperature for *s* = 10.4 mm under terrestrial conditions.

3.2. Results under microgravity

Table 1 shows the results obtained under microgravity, for *s* = 0.3 mm and Table 2 shows the results obtained in the laboratory (*g* = 9.8 m/s²), for the same initial conditions. The heat transfer coefficient under microgravity was approximately 20 % lower than those obtained under terrestrial gravity. This trend occurred for all experimental points analyzed.

Table 1. Experimental results obtained under microgravity, for *s* = 0.3 mm.

q" (kW/m²)	P (bar)	T_{liq} (°C)	T_w (°C)	T_{sat} (°C)	h (kW/m²°C)
20	1.19	29.4	59.3	40.7	1075.3
30	1.24	29.8	72.7	41.9	974.1
40	1.32	31.1	81.1	43.9	1075.5
50	1.38	31.8	86.7	45.3	1206
60	1.45	32.9	94.3	46.8	1301

Table 2. Experimental results obtained under terrestrial gravity, for *s* = 0.3 mm.

q" (kW/m²)	P (bar)	T_{liq} (°C)	T_w (°C)	T_{sat} (°C)	h (kW/m²°C)
20	1.17	25.9	55.6	40.2	1301
30	1.20	26.4	63.5	41.0	1307
40	1.25	26.9	71.7	42.2	1375
50	1.28	27.6	77.4	42.9	1459
60	1.32	28.3	84.3	43.9	1524

Under microgravity, due to the absence of buoyancy and other forces such as natural convection, the vapor bubbles grow sharply over the heated surface and their release is delayed. Without the buoyancy and the constraints of physical space caused by the confinement, the cooling effect is inhibited by the liquid front after the departure of a bubble. This leads to a reduction in the heat transfer coefficient.

Although there is a decrease in the heat transfer coefficient under microgravity, the trends in the partial boiling curves in the two cases are similar, as can be seen in Fig. 9. This is because the natural convection is replaced by transient conduction of the liquid layer, driven by the surface tension gradient, known as Marangoni convection.

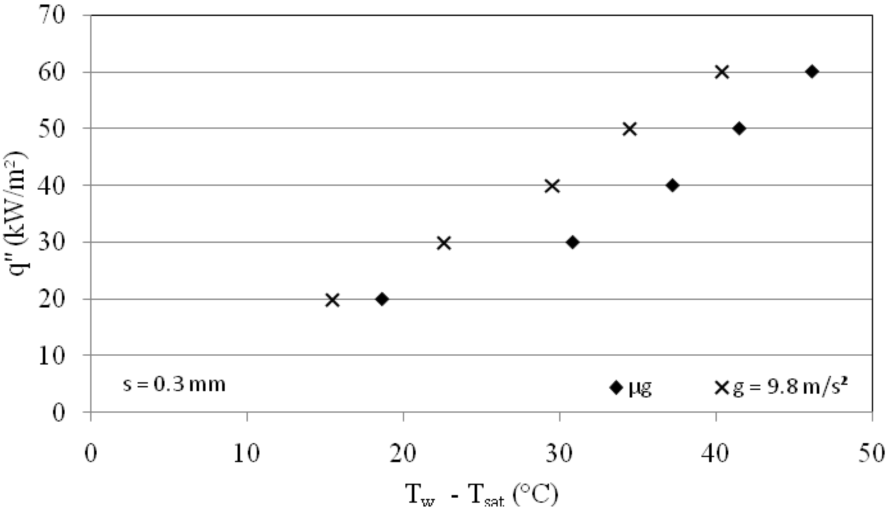

Figure 9. Partial boiling curve for different gravity conditions.

Another important aspect is to analyze the thermodynamic conditions in the absence of gravity and to compare them with the experimental data obtained in the laboratory. Figure 10 shows the temperature variation of the heated surface, for *s* = 0.3 mm, as a function of time for both gravity levels tested. Every 72 seconds, a new heat flux value was used (20, 30, 40, 50 and 60 kW/m²). This time interval was sufficient for the system to enter into the steady state. For heat fluxes higher than 30 kW/m^2, there is a difference in the heated surface temperature of approximately 10 °C.

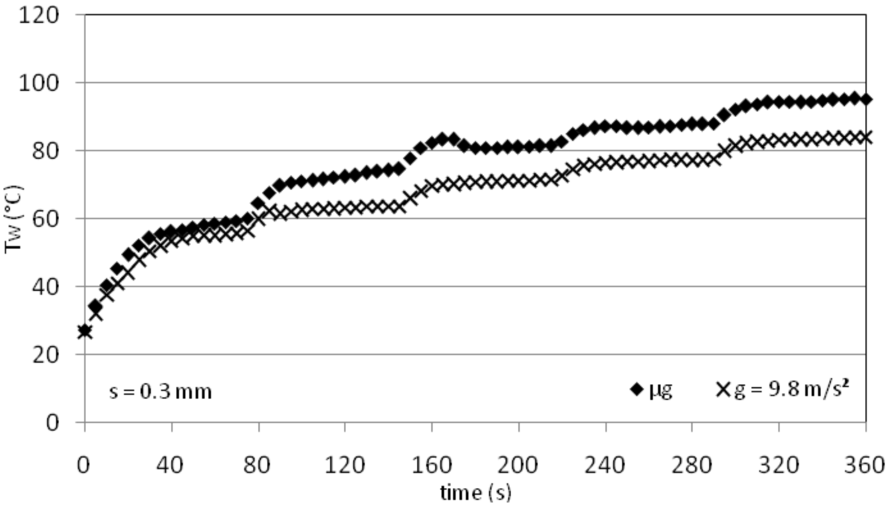

Figure 10. Heated surface temperature variation as a function of time.

Table 3 shows the experimental results for the case without confinement, *s* = 10.4 mm, under microgravity conditions. For this case, the results are different from those obtained in the laboratory. The heat transfer coefficient decreases with an increase in the heat flux. For heat fluxes lower than 40kW/m², the decrease in the heat transfer coefficient is almost linear. However, for a heat flux of 50 kW/m², this decrease is accentuated.

Table 3. Experimental results obtained under microgravity conditions, for *s* = 10.4 mm.

q” (kW/m²)	P (bar)	T_{liq} (°C)	T_w (°C)	T_{sat} (°C)	h (kW/m²°C)
20	1.19	29.2	53.1	40.7	1602
30	1.25	29.4	61.7	42.2	1535
40	1.32	30.8	70.8	43.9	1488
50	1.38	31.2	87.1	45.3	1194
60	1.46	32.6	96.7	47.0	1208

The decrease in the heat transfer coefficient, for s = 10.4 mm and q > 40 kW/m^2, can be explained by the re-wetting of the heated surface. For low heat flux values there is a major flooding of the heating surface, improving the heat transfer. As the heat flux increases, the amount of vapor bubbles on the heating surface increases and dryout begins, causing a reduction in the heat transfer.

4. CONCLUSIONS

An experimental analysis of the effect of microgravity on the partial n-Pentane subcooled boiling curves, using copper discs of 12 mm diameter and a heating surface facing downward, was presented. The main results are the following:

(i) As the confinement decreased, the heat transfer coefficient for subcooled boiling decreased, under the microgravity condition. For the case without confinement, corresponding to *s* = 10.4 and 11.0 mm, the heat transfer was lower than the cases with confinement. For the confined case, the residence time of the vapor bubbles in the gap is smaller. The imbalance between the rates of evaporation and condensation of the vapor-liquid interface was used to explain the decrease in the heat transfer coefficient for subcooled confined nucleate boiling.

(ii) For terrestrial gravity, *s* = 0.9 mm and initial temperatures of 26 and 36 °C, there was only a small effect of the initial liquid temperature on the boiling curve for heat fluxes of 20 and 30 kW/m². For higher heat flux values, there was a ΔT variation of 5 °C. The same trend was observed for *s* = 11.0 mm with initial temperatures of 23.7 and 35.7 °C, *i.e.*, there was an increase in the heat transfer coefficient for the highest initial liquid temperature. However, for *s* = 11.0 mm, the ΔT differences are almost constant for all heat fluxes.

(iii) For *s* = 0.3 mm under microgravity conditions, the heat transfer coefficient was 20 % lower than the values obtained under terrestrial conditions. Without the buoyancy and the constraints of physical space caused by the confinement the cooling effect is inhibited by the liquid front after the departure of a bubble. The consequence is a reduction in the heat transfer coefficient.

(iv) For the case without confinement under microgravity conditions, there was a decrease in the heat transfer coefficient with an increase in the heat flux.

5. ACKNOWLEDGEMENTS

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6. NOMENCLATURE

Bo	Bond number, dimensionless
g	acceleration of gravity , m/s²
h	heat transfer coefficient, W/m²K
L	capillary length, m
q”	heat flux, W/m²
s	characteristic dimension of the confined space, m
T	temperature, °C

Greek symbols	
ΔT	temperature difference, K
ρ	density, kg/m³
σ	surface tension, N/m
Subscripts	
l, liq	liquid
sat	saturation
sub	subcooled
v	vapor
w	wall

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