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Influence of gravity on pool boiling on a flat plate: Results of parabolic flights and ground experiments

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ABSTRACT

Experiments of pool boiling of HFE7000 on a flat plate have been performed in both earth and microgravity conditions in parabolic flights. The effects of pressure, subcooling and gravity are studied. Experiments show that in fully developed boiling regime gravity and subcooling have a weak influence on heat transfer. By identifying mechanisms that control heat transfer, the weak influences of gravity and subcooling are explained.

1. Introduction

The study of boiling in microgravity is of a great interest either for the understanding of the physical mechanisms but also for industrial applications. The present study concerns the heat and mass transfers in the cryogenic tanks of the launchers. A French-German research programme called COMPERE (French acronym for the behaviour of propellants in reservoirs) is dedicated to the upper stage of the European launcher Ariane V. The cryogenic Liquid Oxygen (LOX) or Hydrogen (LH2) are pressurised by their vapour or a non-condensable gas. During the different phases of the mission (propelled phase, ballistic phase) it is important to control the phase distribution and the evolution of temperature and pressure inside the reservoirs. The evolution of these parameters strongly depends on heat and mass transfers. During the ballistic phase of the mission, the tank wall is heated by solar radiation and thermal dissipation due to engine and electrical devices. Since there is no thermal convection in microgravity, the heat transfer between the heated wall and the liquid is mainly due to heat conduction and the wall temperature can become greater than the required temperature for the onset of nucleate boiling. The study of boiling in microgravity is thus of particular interest in this situation. An experimental programme has been developed to study pool boiling on a flat plate in normal gravity and in microgravity conditions in parabolic flights in aircraft. For safety reasons experiments are not performed with cryogenic liquids but with a refrigerant HFE7000.

The study of pool boiling in microgravity has begun in the 60's with the NASA Space programme with experiments performed during short test time by Merte and Clark [1] or Siegel [2]. Contradictory results on the effect of gravity from these earlier experiments have been reported. During the 80's and 90's, experiments on flat heated plates, have been carried out during longer microgravity periods in parabolic flights or sounding rockets by Zell et al. [3], Lee et al. [4], Ohta [5] and Oka et al. [6]. These experiments have shown the existence of stable boiling regimes in microgravity over long periods. In a review of these experiments Straub [7] remarked that gravity has a relatively weak influence on heat transfer in nucleate boiling but it strongly affects the dry out of the heated plate, reducing significantly the critical heat flux in microgravity. Nevertheless the influence of gravity is still not clear; for example experiments performed by Zell et al. [3] and Lee et al. [4] both with R113 on a flat plate gold coated heater do not display the same results: Lee points out an improvement of heat transfer in microgravity whereas Zell observes the opposite trend.

The influence of pressure has been studied by Straub [7], who clearly shows that in earth gravity conditions, an increase of pressure causes an increase of heat transfer. The effect of liquid subcooling on heat transfer has been studied by several authors like Lee et al. [4], Ohta [5] or Oka et al. [6]. Unfortunately in these experiments subcooling was changed by varying the pressure. It is

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Nomenclature

Latin letters

c_p	heat capacity (kJ/kg K)
g	gravity (m/s^2)
g_0	earth gravity (9.81 m/s^2)
h	heat transfer coefficient (W/m^2 K)
h_{lv}	latent heat of vaporisation (kJ/kg)
k	thermal conductivity (W/m K)
$\dot{q}_w$	wall heat flux (W/m^2)
P	pressure (bar)
T_{sat}	saturation temperature (°C)
T_w	wall temperature (°C)
t	time (s)
Z	height above the heater (m)

Greek letters

β	isobaric expansion coefficient (1/K)
ΔT_{sat}	wall superheat, $=T_w - T_{sat}$ (K)
ΔT_{sub}	subcooling, $=T_{sat} - T_l$ (K)
δ_{sat}	superheated liquid layer thickness (m)
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

l	liquid
sat	saturation
v	vapour
w	wall

therefore difficult to distinguish separately the effect of subcooling and pressure on the change in heat transfer.

In the 2000's several experiments performed by Qui and Dhir [8] and Sodtke et al. [9] have been focused on boiling on an isolated nucleation site in order to investigate the local heat transfer at the bubble scale. Original experiments have also been performed by Kim et al. [10], Christopher and Kim [11] using an array of heaters. From these experiments it appears that gravity has no influence on boiling heat transfer in the proximity of the heater where nucleation takes place. They also showed that liquid subcooling and heater size strongly influence the 'dry out' heat flux.

Several correlations exist to predict heat transfer in nucleate pool boiling in earth gravity. These correlations often depend on gravity since the capillary length is taken as a characteristic length scale for the bubble size at detachment. A critical review of the application of these correlations to microgravity conditions was performed by Di Marco and Grassi [12] and Straub [7]. From these correlations we can write the dependency of the wall heat flux on gravity as:

$$\dot{q}_w \propto g^n \tag{1}$$

where n is a constant, which varies from one correlation to the other. In Table 1, the value of the exponent is given for different usual correlations. Except for the correlation of Cooper [13], most of the usual correlations anticipate a very low heat flux in microgravity, which is not in agreement with the experimental results. So, these correlations are not adequate to estimate the heat flux in microgravity and it is more relevant to use g as a constant equal to its value on earth, as suggested by Dhir [14].

From the previous works it appears that the influence of different parameters like gravity or subcooling remains unclear. In the present study, new experimental results are given and a new approach of boiling phenomenon is proposed in order to clarify the understanding of boiling typically concerning the influence of gravity on boiling heat transfer.

Table 1
Gravity dependency of correlations.

Correlations	n	$\frac{\dot{q}_w(g=10^{-2}g_0)}{\dot{q}_w(g=1g_0)}$	$\frac{\dot{q}_w(g=10^{-5}g_0)}{\dot{q}_w(g=1g_0)}$
Rohsenow [18]	0.5	0.1	3.2×10^{-3}
Cooper [13]	0	1	1
Stephan and Abdelsalam [19]:			
Water	1.48	1.1×10^{-3}	4×10^{-8}
Hydrocarbons	−0.25	3.16	17.8
Cryogenics	0.38	0.17	1.3×10^{-2}
Refrigerants	0.5	0.1	3.2×10^{-3}

The experimental set-up and measurement techniques are first presented. The experimental results obtained in microgravity are compared to experiments performed on ground with the same set-up. The results in microgravity are also compared to other data of the literature with refrigerants. Finally, the influence of gravity, pressure and subcooling on the boiling regimes and heat transfer is highlighted.

2. Experimental set-up and operating conditions

The experimental set-up is designed to perform boiling experiment in different conditions of pressure and subcooling [15]. These two parameters can be fixed independently. The test cell is connected to two tanks, one at high pressure, and the other one at low pressure. The pressure inside the test cell is controlled by a relief valve connected to a pressure regulator. The pressure relief valve connects the test cell to the low pressure tank and controls the test cell pressure with an accuracy of 10 mbar. The temperature in the test cell and in the two tanks is adjusted and kept constant by three resistive heaters and a water cooling system. The two tanks are partially filled with liquid so that their pressure is the saturation pressure given by their mean temperature. The fluid is fully degassed before starting the experiment.

2.1. Test cell and measurement techniques

The test cell (Fig. 1) is devoted to the study of pool boiling on a flat plate at different pressures and different temperatures. It was machined in an aluminium block. It contains a volume of 0.7 L between the heater and the bottom of the test cell. A magnetic stirrer is used to mix the fluid and homogenise the temperature. In the upper part, four windows (in blue) are located on the lateral walls for the visualisations.

The wall temperature and heat flux are measured by a Captec heating element (Fig. 2, www.captec.fr). Temperature and heat flux are measured in a mid plane (properly the heat flux meter) and heating is provided at the back side (resistive heater). A 30 μm thick copper layer facing the fluid offers a surface finish comparable to actual surface in boiling systems. The size of the heating plate is 1cm square. The thickness of the heater is 0.4 mm. Copper layer and flux meter are separated by a polyamide layer 150 μm thick.

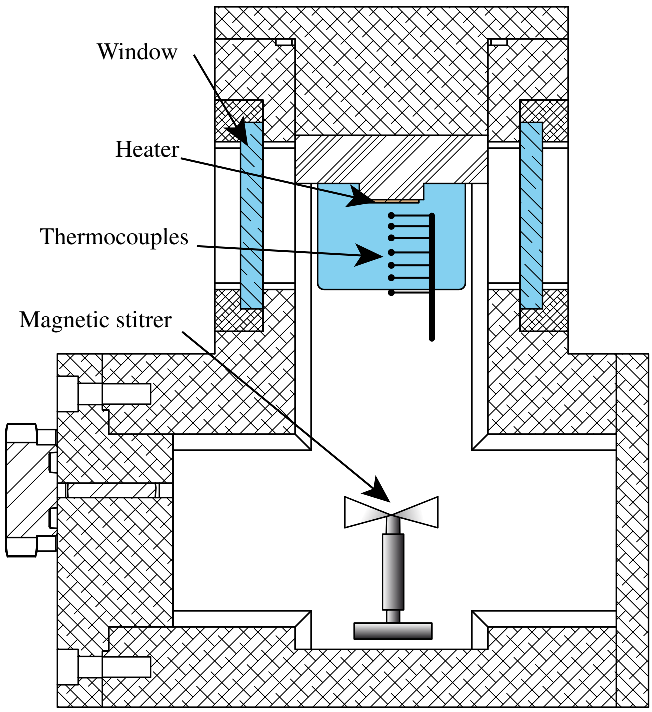

Fig. 1. Test cell.

As we are interested in the temperature and heat flux at the heating surface of the heater (copper layer), it is necessary to have a model relating them to temperature and heat flux measured in the flux meter plane. In steady state condition, estimation of the thermal resistance between the copper layer and the heat flux meter is sufficient. In transient measurements, a Laplace Thermal Quadrupole model can be used. The response time of the heating system has thus been estimated to be about 2 s. Thermal equilibrium is thus rapidly reached when compared to the duration of microgravity periods, and the thermal resistance model provides a good prediction of heat transfer in the heater. Finally the wall temperature is measured with an accuracy of ±0.5 K and the wall heat flux with an accuracy estimated at ±10%.

In the vicinity of the heating element, seven thermocouples of type K are used to measure fluid temperature. The four nearest to the heating wall have a 50 μm junction (response time of 0.15 s), and the three last a 1 mm junction. Distances between the heating wall and the thermocouples, are 0.05, 1.08, 3.4, 5.48, 10.08, 13.61, and 20 mm.

Temperatures and heat flux measurements are recorded by two KUSB3108, which are multiplexed high gain voltmeters that guarantee low noise and high frequency measurements.

The pictures of the bubble layer on the heating plate have been recorded by a high-speed camera (PCO1200HS, 1024 × 1280 px, 133 Hz) and image processing gives information on the bubble population (behaviour, size, and number).

2.2. Experimental parameters and operating conditions

Experiments have been performed in microgravity conditions in parabolic flights. During each parabola a period of 20 s with residual gravity levels smaller than $3 \times 10^{-2} g_0$ (g_0 being the terrestrial gravity) are obtained. Additional experiments are also performed in laboratory with the heating plate upward facing and downward facing to point out the gravity effect on heat transfers. The fluid used for the experiments is the 3M Novec HFE7000 (methyl perfluoropropyl ether). Properties of this fluid for different pressures are given in Table 2.

During the microgravity experiments, steady state boiling is studied. Bulk pressure and temperature range from 1 to 3 bar, and from 30 to 70 K, respectively corresponding to subcooling between 1 and 19 K. Heat fluxes are in the range 2–35 kW/m^2.

In these experiments, boiling incipience occurs before entering the microgravity period. In Fig. 3 acceleration, g, heat flux, $\dot{q}_w$, and

Table 2
HFE7000 properties.

P (bar)	1	2	4	8
T_{sat} (°C)	35	56	80	107
ρ_l (kg/m^3)	1386	1323	1245	1141
ρ_v (kg/m^3)	8.26	16.05	31.85	66.2
k_l (W/m K)	72.9×10^{-3}	68.8×10^{-3}	64.1×10^{-3}	58.6×10^{-3}
$c_{p,l}$ (kJ/kg K)	1.331	1.396	1.470	1.556
h_{lv} (kJ/kg)	131.82	123.30	112.133	96.123
μ_l (Pa s)	3.72×10^{-4}	2.83×10^{-4}	2.056×10^{-4}	1.394×10^{-4}
σ (N/m)	11.4×10^{-3}	9.36×10^{-3}	7.01×10^{-3}	4.27×10^{-3}
β_l (1/K)	2.19×10^{-3}	2.41×10^{-3}	2.69×10^{-3}	3.59×10^{-3}

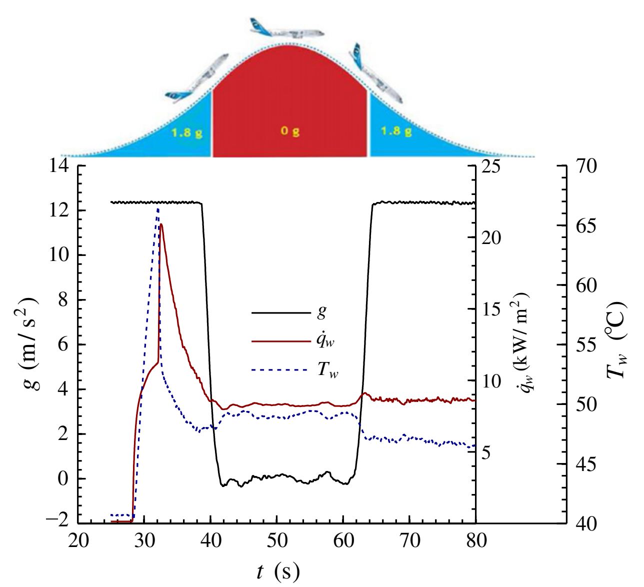

Fig. 3. Measurements of gravity, g, heat flux, $\dot{q}_w$, and wall temperature, T_w during a parabola.

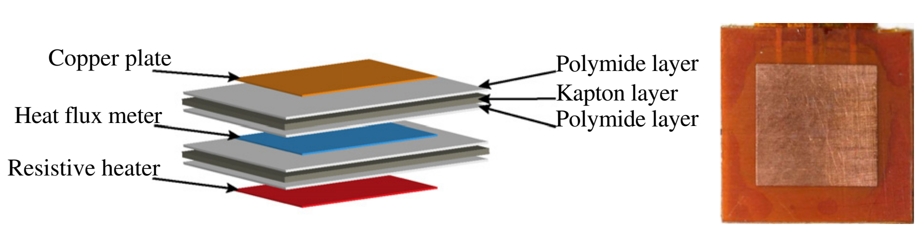

Fig. 2. Heating element.

wall temperature, T_w, variations during one parabola are plotted versus time. At the beginning of the parabola, the acceleration is larger than 12 m/s^2. During this period, the heater is powered on to reach the onset of boiling (t = 30 s). Heating is then lowered gently to keep a moderate boiling when entering the microgravity period (t = 40 s). Heat flux and wall superheat reach quite rapidly a steady value (t = 42 s). After the microgravity period, if the heat flux is maintained at the same value, wall superheat decreases, i.e. heat transfer is enhanced.

3. Experimental results in microgravity

In Fig. 4, the time evolution of gravity and wall superheat are plotted during one parabola. We can see that during the periods of negative acceleration, bubbles detach from the wall, while during the periods of positive acceleration, bubbles remain attached to the wall and we observed a strong coalescence. During the parabola presented in this figure, the wall superheat fluctuates in a range of 1 K in opposition with gravity. Thus, bubble detachment seems to reduce heat transfer.

The maximum of the cross-correlation function between the gravity level and the wall superheat has been calculated for the different runs. Its value is close to −0.8 and corresponds to a time ranging between 0 and 1 s, which is characteristic of the response time of the heater. It proves that the fluctuations of the wall superheat are directly related to g-jitter. Nevertheless the RMS value of the heat transfer coefficient $\sigma(h)$ scaled by $\bar{h}$, the mean heat transfer coefficient over a parabola (Fig. 5), remains smaller than 0.25. It decreases quickly with the wall superheat and becomes smaller than 10% for ΔT_{sat} > 5 K.

3.1. Boiling curves in microgravity

Fig. 6 represents boiling curves obtained for a pressure around 1 bar and for different subcoolings. In this figure, pictures representing typical bubble sizes during boiling are also reported. At low subcooling (squares), it clearly appears that the density of bubbles on the heater and their size rapidly increase with the heat flux. The heater is completely covered by bubbles for a wall superheat of about 8 K.

For a heat flux of 25 kW/m^2, boiling pictures for subcoolings of about 2 K and 10 K are presented. We can see that subcooling strongly influences the bubble sizes. As explained by Kim et al. [10], the bubble size in microgravity results from the competition between evaporation at the bubble foot and condensation at its cap. Increasing subcooling, enhances condensation and leads to smaller bubbles. Despite the strong influence of subcooling on bubble sizes, the heat flux measured in subcooled boiling is about the same as this measured in saturated boiling for all our data, but not for the subcooled boiling measured at q_w = 26 kW/m^2. However this last measure was performed at a pressure 0.15 bar above the measured pressure for saturated boiling. Then, the influence of subcooling at high heat flux remains unclear. At least, subcooling has a weak influence on heat transfer at low heat flux while it has a strong influence on bubble size.

Boiling curves for P = 1 bar and ΔT_{sub} = 2 K (square), for P = 1.7 bar and ΔT_{sub} = 3 K (cross) and for P = 3 bar and ΔT_{sub} = 10 K (circle) are plotted in Fig. 7. Boiling curves show a higher heat transfer for P = 1.7 bar and ΔT_{sub} = 3 K than for P = 1 bar and ΔT_{sub} = 2 K, which is clearly visible at high heat flux. The difference of subcooling between these two boiling curves is very weak and the enhancement of heat transfer between these two cases is due to pressure variation. From the two boiling curves for P = 3 bar and ΔT_{sub} = 10 K, and P = 1 bar and ΔT_{sub} = 2 K, we find that the heat transfer is increased by a factor 2 as long as ΔT_{sat} < 10 K, and above this value, this trends vanishes (note that subcooling had a weak influence on heat transfer for this range of wall superheat so this is the pressure increase which also explains the difference of heat transfer between these two last cases). The effect of pressure is well known in earth gravity boiling and was also studied on a small heater in microgravity by Straub [7] showing the same influence of pressure.

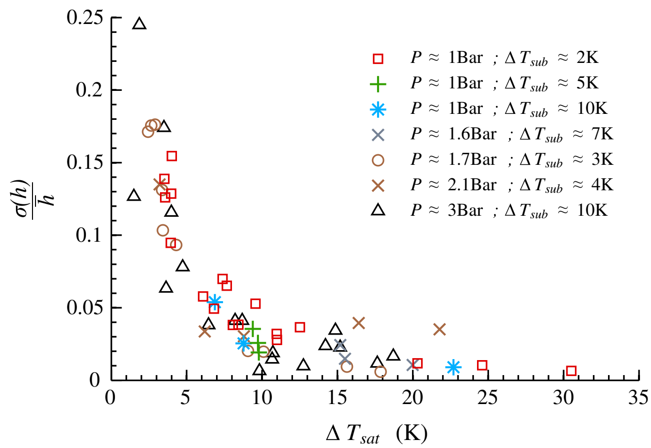

Fig. 5. Normalized fluctuation of heat transfer, $\frac{\sigma(h)}{\bar{h}}$, versus wall superheat.

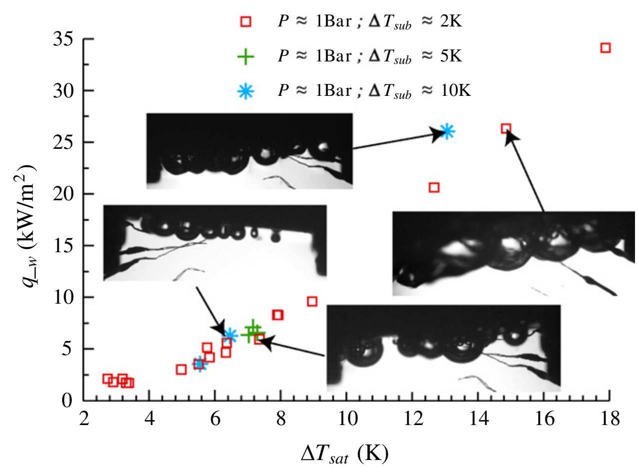

Fig. 6. Boiling curves for different subcoolings in microgravity, $g = 1 \times 10^{-2} g_0$.

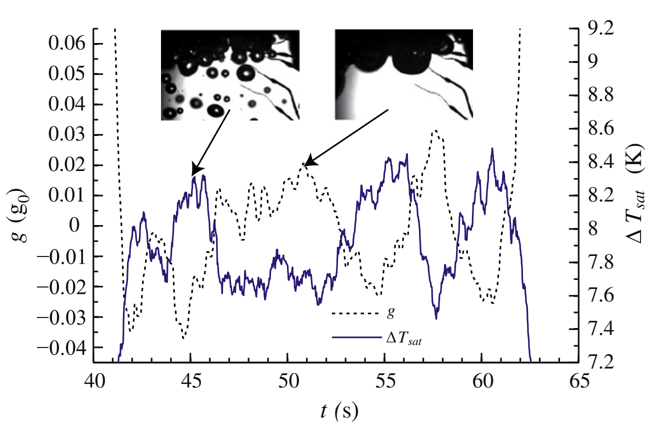

Fig. 4. Influence of g-gitter on boiling.

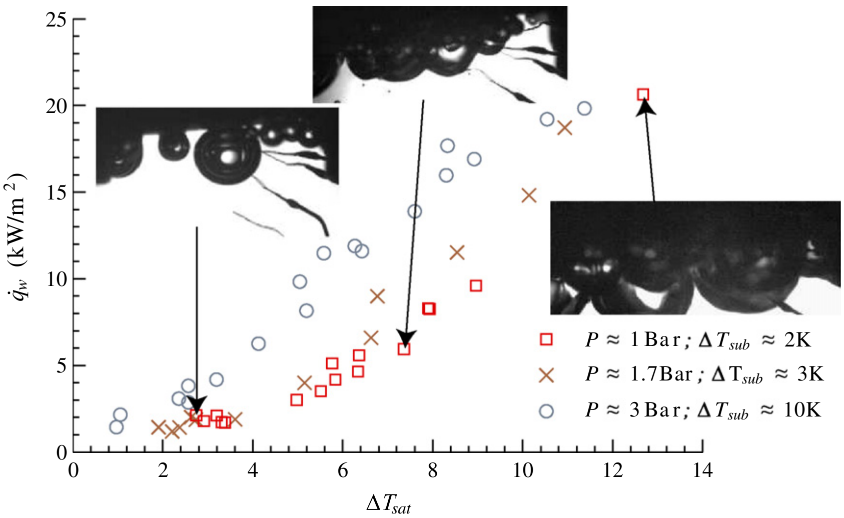

Fig. 7. Boiling curves for different pressures.

3.2. Temperature in the liquid phase

Temperatures in the liquid phase above the heater are averaged over the microgravity period for each parabola. In Fig. 8, the difference between the liquid temperature T_l and the wall temperature T_w is plotted as a function of the distance to the wall, Z, for different subcoolings but same heat flux and same pressure: 3.7 K for the squares and 13 K for the stars. We note that in the direct vicinity of the heater (50 μm from the surface), subcooling has no effect on liquid temperature.

In Fig. 9, the same graphic is presented for two cases at different subcoolings and pressures. For these two cases we can see that $T_l - T_w$ is different at 50 μm from the wall. As subcooling has no influence on $T_l - T_w$ at this location, pressure is thus responsible for this effect.

Using these temperature measurements, we roughly estimate the height of liquid, δ_{sat}, at which the temperature is equal to the saturation temperature. To obtain this value we assume a linear profile of temperature in the liquid between this thermocouple and the wall. This value, δ_{sat}, is referred as the superheated liquid layer thickness.

The average value of δ_{sat} for the different runs is plotted in Fig. 10 versus the wall heat flux, $\dot{q}_w$. For the measurements performed at 1 bar, the superheated liquid layer thickness decreases while heat flux increases. This can be explained because the bubble density on the heater increases in the same way and the evaporation becomes more efficient in the superheated liquid layer. The

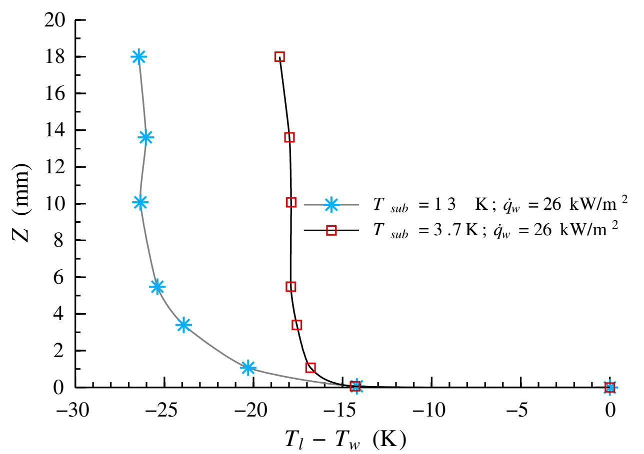

Fig. 8. Temperature profiles above the heater for different subcoolings, $P = 1$ bar.

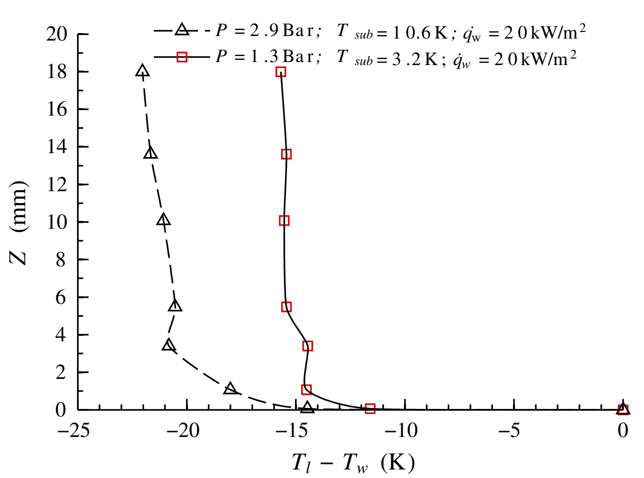

Fig. 9. Temperature profiles above the heater for different subcoolings and pressures.

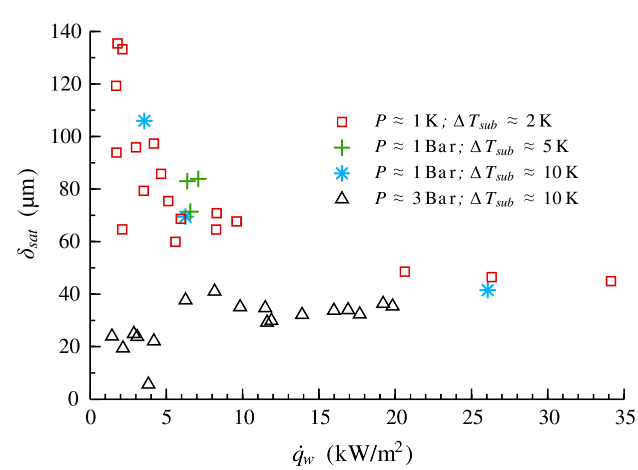

Fig. 10. Thickness of the superheated liquid layer versus the wall heat flux in microgravity.

value of δ_{sat} for $P = 1$ bar and $\Delta T_{sub} = 5$ K and $\Delta T_{sub} = 10$ K are very close to the value of δ_{sat} for $P = 1$ bar and $\Delta T_{sub} = 2$ K. So the subcooling which has a weak influence on boiling heat transfer as also a weak influence on the superheated layer thickness. For $P = 3$ bar and $\Delta T_{sub} = 10$ K we observe that δ_{sat} is always smaller than for $P = 1$ bar showing that the increase of pressure enhances evaporation efficiency in the superheated liquid layer. So the thickness of the superheated liquid layer is well related to the boiling heat transfer. The higher the wall heat transfer, the smaller is the value of δ_{sat}.

We have seen that subcooling has a strong influence on bubble size, while its influence on heat transfer and on the superheated liquid layer thickness is much weaker. The bubble size which is usually used as the length scale for boiling heat transfer correlations does not seems to be correlated to boiling heat transfer in microgravity, while δ_{sat} does.

In the Fig. 10 we can observe that variations of estimated δ_{sat} with wall heat flux disappear when it approaches 50 μm. This value corresponds to the distance from wall of thermocouple T1. This thermocouple possesses a hot junction which is approximately spherical with a radius of about 25 μm. When the limit of the superheated liquid layer is on this hot junction or below, the estimation of δ_{sat} is certainly strongly biased. Nevertheless, the qualitative comparison of δ_{sat} at different pressure is relevant.

Fig. 10 shows that subcooling has no influence on δ_{sat} as it has no influence on the wall heat transfer. The value of δ_{sat} is smaller when the pressure is higher (3 bar) showing that the increase of pressure enhances evaporation efficiency in the superheated liquid layer. The thickness of the superheated liquid layer is directly related to the wall heat transfer. The higher the wall heat transfer, the smaller is the value of δ_{sat}.

4. Experimental results in earth gravity

4.1. Upward facing plate

In Fig. 11, the boiling curves in earth gravity conditions are plotted for an upward facing heater for 2 pressures and 2 subcoolings. The increase in pressure clearly enhances heat transfer independently of the wall superheat. The influence of subcooling on heat transfer is strong at low wall superheat but its influence decreases while increasing heat flux.

At low wall superheat ($\Delta T_{sat} < 20$ K), nucleate boiling is in an isolated bubble regime. In such a regime, density of nucleation sites is weak and mechanism like natural convection takes place on a large part of the heater. When wall superheat increases the density of nucleation sites strongly increases until the larger part of energy taken from the wall is due to bubble formation and detachment. This is the fully developed boiling regime where evaporation is the most important mechanism of heat transfer and the nucleation site density is limited by the bubbles themselves. In this regime, subcooling looses its influence, showing that it has a weak influence on the global evaporation rate.

4.2. Downward facing plate

Fig. 12 represents boiling curves in earth gravity condition for a downward facing heater for the same conditions of pressure and subcooling as before. In this configuration pressure has the same effect on heat transfer. The influence of subcooling disappears at a lower wall superheat than when the heater is facing upward. Moreover in this configuration at low wall superheat, the heat flux is higher when subcooling is weaker. When the heater is downward facing, there is a very weak natural convection, and the heater is most of the time covered by a large bubble so that it is isolated from the cold liquid. Evaporation is the main mechanism of heat transfer: the boiling is even at low heat flux in fully developed regime and subcooling looses its influence on heat transfer.

A possible explanation is that subcooling has caused, in this particular case, heat transfer to decrease at low heat flux because during period of rewetting of the surface the cold liquid deactivates the nucleation sites. As evaporation is the most important mechanism of heat transfer, by decreasing nucleation site density the subcooling has decreased heat transfers at the wall.

4.3. Influence of gravity on boiling regimes and heat transfers

In Fig. 13, the effect of gravity on heat transfer is highlighted. In this figure, boiling curves are plotted for $P \approx 1$ bar and $\Delta T_{sub} \approx 3$ K and for different levels of gravity and heater orientations. For $\Delta T_{sat} < 20$ K the boiling curve for $g = 1g_0$ (heater upward facing) indicates a heat transfer lower than for $g = -1g_0$ (heater downward facing) and $g = -1.5g_0$. For this range of wall superheat, when the heater is upward facing boiling is in the regime of isolated bubbles, while it is in fully developed regime when it is downward facing. So, in this case, the difference of heat transfer coefficient can, at least partially, explained by a difference of regime. We have seen that the influence of subcooling becomes weak on the boiling curve for $P = 1$ bar, the heater upward facing for $\Delta T_{sat} > 20$ K. For this same range of wall superheat, we also observe that the influence of gravity on heat transfer is weaker than at lower wall superheat.

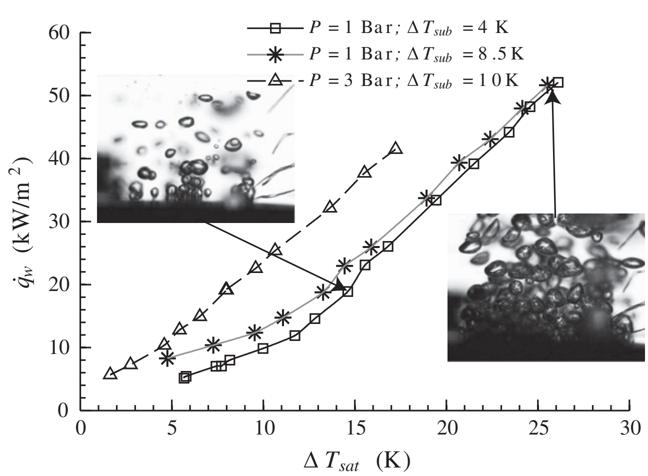

Fig. 11. Boiling curves in earth gravity, heater facing upward.

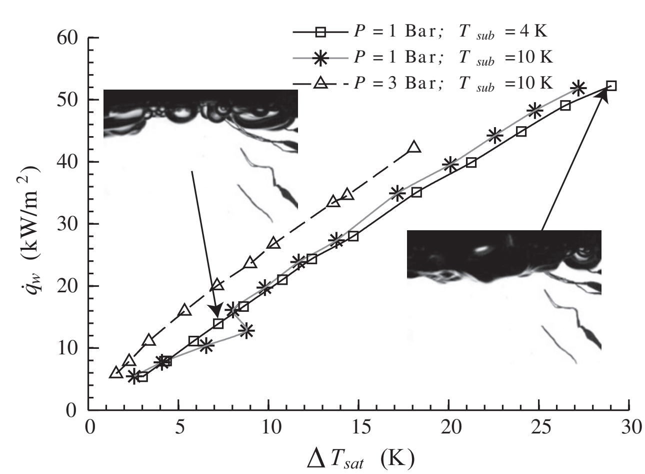

Fig. 12. Boiling curves in earth gravity, heater facing downward.

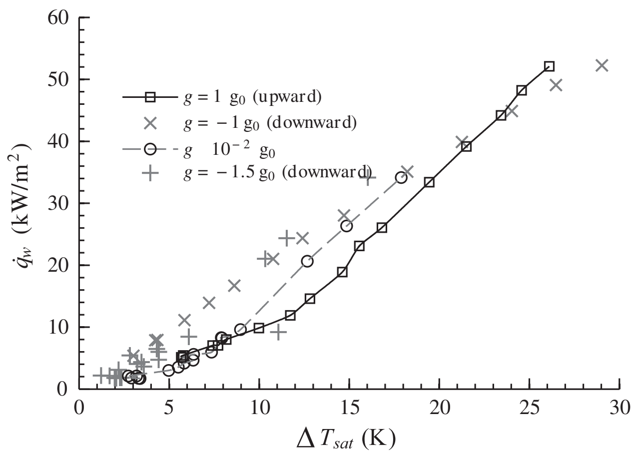

Fig. 13. Boiling curves for different levels of gravity, $P = 1$ bar and $\Delta T_{sub}K < 4$ K.

For $\Delta T_{sat} > 20$ K the boiling for the heater upward facing and downward facing is in the fully developed regime. Gravity and subcooling have always a strong influence on the boiling pattern (bubble size, bubble detachment, etc.). So in fully developed regime the boiling pattern is not correlated to heat transfer.

The boiling curve in microgravity is always under the boiling curves for $g = -1g_0$ and $g = -1.5g_0$ but the difference between this three curves decreases while wall superheat increases. For this three cases, boiling reaches the fully developed regime at very low wall super heat. Thus in fully developed regime, the influence of gravity on heat transfer decreases when wall superheat increases.

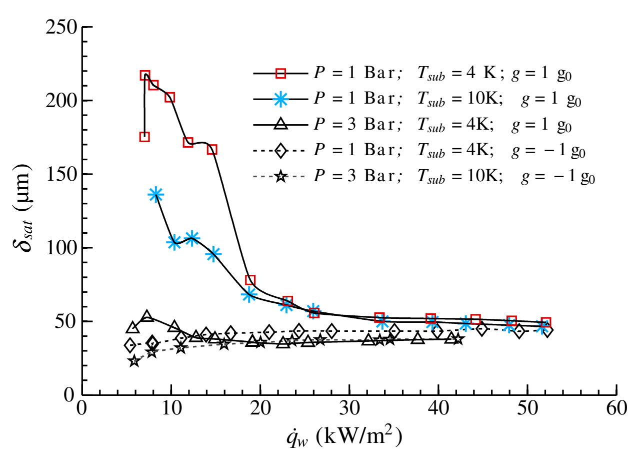

Fig. 14. Thickness of the superheated liquid layer versus wall heat flux in earth gravity.

The Fig. 14 represents δ_{sat} versus the wall heat flux for experiments performed in earth gravity condition, heater facing upward and downward for different conditions of pressure and subcooling. When we compare the value of δ_{sat} for a pressure of 1 bar heater facing upward for the two subcoolings, the subcooling has an influence on heat transfer at low heat flux but this influence disappears at higher heat flux when the regime is fully developed. At low heat flux, heat transfer is higher in subcooled condition and this can clearly be seen in this figure by a smaller thickness of the superheated liquid layer.

Gravity has an influence on heat transfer at low heat flux and this influence can also be seen on δ_{sat} in the same way as the subcooling. When we compare the curves for the upward facing heater (square) and the downward facing heater, at high heat flux, for fully developed regime ($\dot{q}_w = 25\ \mathrm{kW/cm^2}$), gravity has a weaker influence both on heat transfer and on δ_{sat}. So the superheated liquid layer thickness is a more relevant length scale to characterise boiling heat transfer than the classical length scale (bubble size, capillary length) found in the literature.

5. Heat transfer mechanisms for nucleate boiling

Straub [7] proposed to divide the mechanisms controlling heat transfer during nucleate boiling in two groups: the primary mechanisms and secondary mechanisms.

The primary heat transfer mechanisms (Fig. 15) occur in the superheated layer: advection in the liquid, thermal conduction from the wall, evaporation at the bubble interface including micro-layer evaporation beneath the bubble foot. These mechanisms directly control heat transfer at the wall.

In the secondary mechanisms (Fig. 16) we include all the mechanisms transferring energy from the near wall region to the liquid bulk far from the wall. Energy is stored by primary mechanisms in the superheated layer (as specific heat or latent heat in the vapour phase), then it is transferred to the bulk by the secondary mechanisms: bubble detachment, enhanced convection by bubble detachment, natural convection and condensation at the bubble cap.

The thickness of the superheated liquid layer can be interpreted as a measurement of the efficiency of the primary mechanisms as long as it results from the balance of the diverse primary mechanisms. We have already seen that in the fully developed boiling regime this thickness as well as heat transfer at the wall are not influenced by gravity and subcooling. But gravity has an effect on bubble detachment and subcooling influences condensation at the cap of the bubble. It means that these two parameters play a role only on the secondary mechanisms. We conclude that in fully developed boiling, the heat transfer at the wall is related to the

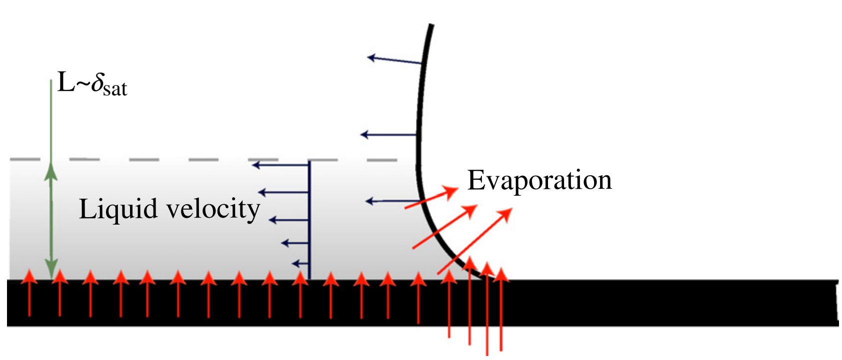

Fig. 15. Primary heat transfer mechanisms.

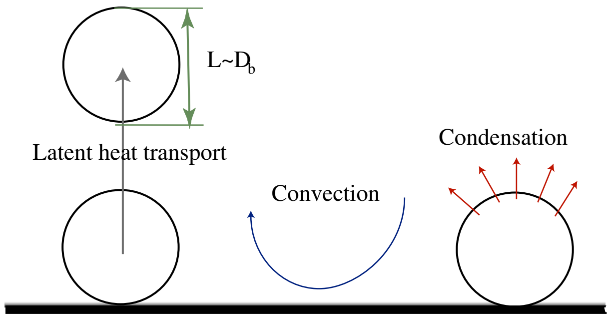

Fig. 16. Secondary heat transfer mechanisms.

primary mechanisms which are the limiting mechanisms; the secondary mechanisms transfer heat from the vicinity of the wall to the fluid without limitation.

Primary mechanisms have a typical length scale very small, of the order of magnitude of δ_{sat}: it explains why gravity, which is a volume force has a weak influence on heat transfer. For secondary mechanisms the relevant length scale is rather related to the bubble size or the capillary length. The correlations for predicting heat transfer in nucleate boiling are often based on the secondary mechanisms and thus the chosen length scale is the capillary length.

In microgravity, evaporation is the main mechanism of heat transfer and even at low heat flux boiling is in a fully developed regime. In this situation the wall heat transfer is controlled by the primary mechanisms and it is not correlated to the secondary mechanisms. It explains why usual correlations of the literature based on the capillary length, which is characteristic of the secondary mechanisms, are unable to predict heat transfer in microgravity.

6. Boiling regimes

Secondary mechanisms do not have influence on heat transfer in fully developed boiling regime. Nevertheless these mechanisms have an influence on the limits between this regime and the isolated bubble regime and between this regime and the 'dry out' heat flux.

For example, for a negative gravity (heater facing downward) the wall superheat at which fully developed boiling is reached is lower than when gravity is positive.

The influence of secondary mechanism on the dry out heat flux seems to be obvious. 'Dry out' heat flux is reached when there is too much vapour in the near wall region and some part of the heater is dried out. By definition removal of this vapour phase is ensured by secondary mechanisms.

For example, Lee et al. [16] reported that in microgravity condition for low subcooling condition ΔT_{sub} = 2.7 K, 'dry out' of the heater occurred for $\dot{q}_w < 40$ kW/m^2 while for ΔT_{sub} = 22 K a heat flux of 80 kW/m^2 could be reached without 'dry out' (in this article it is reported that steady state boiling could be reached at such a heat flux with a high subcooling, on the opposite, no steady state condition showed that 'dry out' occured implicating an increase of wall temperature). These limits of heat flux are much lower than what can be obtained in earth gravity conditions.

The fact that 'dry out' heat flux is lower in microgravity condition explains the difference between experiments of Zell et al. [3] and Lee et al. [4]. Fig. 17 shows the comparison of two boiling curves in earth and microgravity conditions obtained by these two authors. This figure shows that heat transfer is enhanced in microgravity for Lee et al. [4] while it is deteriorated for Zell et al. [3]. For this last experiment, it is reported that the foot of the primary bubble was increasing in size during the experiment and the authors have never observed a stable wall temperature.

At a heat flux of about 40 kW/m^2, the boiling curve in microgravity of Zell et al. [3] takes a low slope and at the same value of heat flux the boiling curve of Lee et al. [4] takes also a low slope and crosses the boiling curve in earth gravity condition. At this value of heat flux, the two authors have reached the 'dry out' heat flux. In the experiment of Zell et al. [3] the boiling curve in microgravity condition is under the boiling curve in earth gravity condition because most of the measurements have been performed above the 'dry out' heat flux. For this last experiment, on Fig. 17, nucleate boiling in earth gravity condition is compared to boiling in microgravity in a regime equivalent to film boiling.

We can notice in Fig. 17 that our measurements performed in microgravity are lower than 40 kW/m^2. The liquid in our experiment has physical properties close to that of R113. As gravity fluctuations were 1000 times greater during our experiments than in the experiments of Zell et al. [3] and Lee et al. [4], our measurements were performed below the CHF heat flux.

Fig. 18 represents schematically the influence of heat flux and gravity on boiling regimes. The limits between the different regimes are influenced by secondary mechanisms and also probably

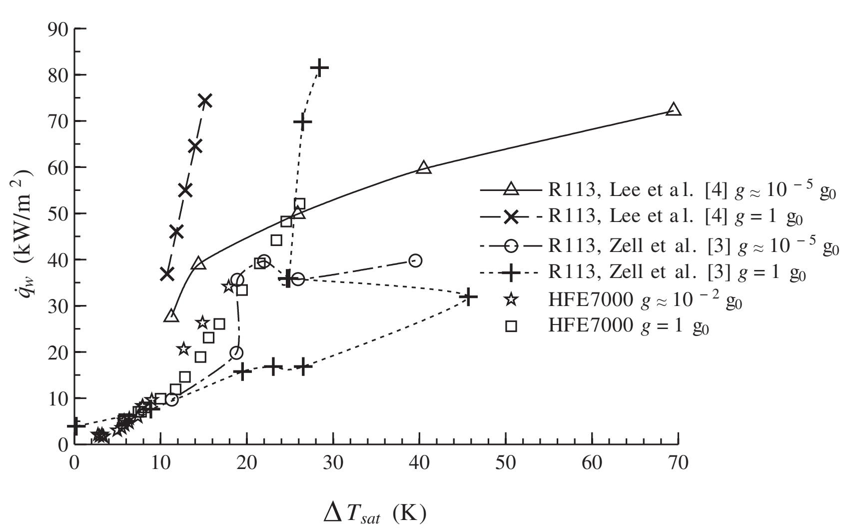

Fig. 17. Boiling curves in earth gravity and microgravity from Zell et al. [3] and Lee et al. [4], liquid, R113, and from the current study, liquid, HFE7000, at a pressure of about 1 bar and subcooling of about 10 K.

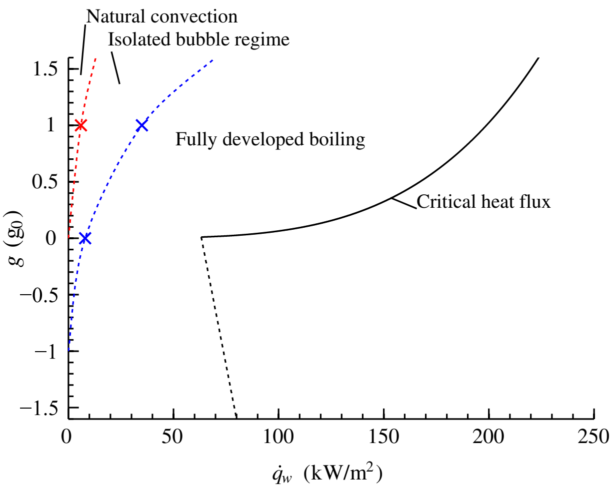

Fig. 18. Boiling regimes in term of gravity and heat flux, dashed line are suggested and passes through our measurements (crosses).

by parameters like wall roughness or heater size. Gravity is responsible for drastic changes in the heat transfer regimes.

The limit at high heat flux of the fully developed boiling regime is given in this figure by the correlation of Lienhard and Dhir [17]:

$$\dot{q}_C = 0.149\rho_v^{1/2}h_{lv}[\sigma g(\rho_l - \rho_v)]^{1/4}$$

where $\dot{q}_C$ is the critical heat flux. This expression does not take account for subcooling but experimental results in microgravity show that its influence is important on $\dot{q}_C$. This is why we have chosen not to extrapolate this line for gravity level lower than $10^{-2}g_0$. This line is extended by a dashed line for negative gravity: we do not have information on the trend (see Fig. 18). In this domain as in microgravity, the heater size must have a strong influence.

The limit between isolated bubble regime and fully developed boiling remains also not defined. From our measurements we have determined it for a pressure of 1 bar and $g = 1g_0$ and $g \approx 10^{-2}g_0$. The limit between natural convection and isolated bubble regime is given for $g = 1g_0$ when boiling stops while decreasing heat flux.

This graph shows that in microgravity for a wide range of heat flux, $\dot{q}_w \in [8; > 35]$ kW/m^2, the boiling regime is fully developed. In earth gravity condition for $\dot{q}_w \in [5; 35]$kW/m^2, boiling is in the isolated bubble regime. So comparing boiling in earth gravity with boiling in microgravity for this range of heat flux means comparing two different regimes, and this comparison is maybe not relevant.

7. Conclusion

Experimental results on pool boiling on a heated plate have been presented for different plate orientations and gravity levels. The influence of gravity, pressure and liquid subcooling is clearly pointed out and depends on the observed boiling regime. Two regimes are identified: an isolated boiling regime and a fully developed boiling regime.

From our experiments performed in microgravity we have noticed that heat transfer is controlled by local mechanisms taking place in the heater vicinity. In earth gravity condition, this behaviour appears at high wall superheat when boiling is in the fully developed regime.

From this conclusion we divide mechanisms of heat transfer as proposed by Straub [7] in two categories:

- primary mechanisms, responsible of the heat transfers in the vicinity of the wall;
- secondary mechanisms, responsible for removing energy from the vicinity of the wall.

In fully developed boiling, primary mechanism efficiency is not limited by secondary mechanism. That explains why correlations based on the capillarity length are unable to predict heat transfer in microgravity.

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