Pressure drop and void fraction during flow boiling in rectangular minichannels in weightlessness

D. Brutin, V.S. Ajaev, L. Tadrist

Aix-Marseille University, IUSTI UMR 7343 CNRS, Marseilles, France
Southern Methodist University, Department of Mathematics, Dallas, TX 75275, USA

HIGHLIGHTS
- Microgravity frictional pressure loss is half of value at normal gravity.
- Hypergravity frictional pressure loss is 1.3 times higher than at normal gravity.
- Increase in pressure drop is explained by decrease of void fraction with gravity.
- Bubble departure diameters are strongly influenced by gravity.
- Void fraction changes along the channel for different gravity levels.

ABSTRACT
An experimental investigation has been carried out on flow boiling in a minichannel to explain heat transfer enhancement observed experimentally under the conditions of weightlessness. The analysis is based on the local void fraction and frictional pressure loss measurements. Frictional pressure loss in two-phase flows in minichannels under terrestrial gravity is described by several well-known correlations. In weightlessness, however, few experimental results are available on the void fraction and the frictional pressure loss. The experiments for this study have been performed at constant heat flux supplied to the minichannel with inlet liquid mass velocity ranging between 30 and 248 kg s⁻¹ m⁻². The influence of hypergravity (gravity level of 1.8g) and microgravity (gravity level of approximately 0.05g) on the frictional pressure loss is observed and explained using the flow patterns visualization and experimental void fraction determination through image treatment. Pressure drops for two-phase flow in microgravity are found to be significantly higher than for single-phase flow under similar conditions; possible explanations for the difference are discussed. The experimental thermal measurements have been previously analyzed using inverse techniques which led to evaluation of the local heat transfer coefficient. The heat transfer enhancement observed during weightlessness is explained in the present work by investigating the differences in flow patterns and void fraction under different levels of gravity.

1. Introduction

Flow boiling in minichannels can lead to significant heat transfer enhancement compared to single-phase liquid flow under similar conditions [12,19,22]. The confinement effect on the vapor generated due to phase change has been known to result in the pressure drop fluctuations observed in many experimental studies. The first investigations of convective boiling in microgravity were conducted at NASA back in the 1970's [3]. The studies aimed at understanding the mechanisms of coalescence in two-phase flows were mostly conducted over the past 15 years (see Table 1). The
advantage of heat transfer with liquid–vapor two-phase flow is obvious from the comparison between the heat transfer coefficients in flow boiling and in single phase heat transfer. Many industrial communities are interested in heat recovery and heat transfer enhancement. In applications to space technology, not only the performance under conditions of reduced gravity but also the size of the heat exchanger is important. Studies of heat transfer in small-scale systems during pool and flow boiling under reduced gravity conditions indicate that the heat transfer coefficient can be either higher or lower than under normal gravity, depending on the system configuration. Experiments performed in microgravity help to understand the flow phenomena when gravity is no longer acting. They reveal new leading mechanisms that are underestimated or hidden on Earth. The implications are wide for industrial systems using phase change heat transfer.

Colin et al. [4] present results obtained for air–water flows in microgravity by parabolic flights. The test section consists of a tube of 40 mm in diameter and 317 mm in length. These authors observe that the phenomena of bubble coalescence differ from the case of two-phase flow under terrestrial gravity and attribute the difference to a higher rate of turbulence in microgravity. Zhao & Rezkallah [5] analyze the transitions between different modes of two-phase flow in microgravity for an air–water mixture. They find that the Weber number of the gas phase constitutes a good indicator for the transition between annular and slug flow. Bousman et al. [6] study the influences of speeds of gas and liquid as well as interfacial tension on the flow structure in microgravity for water–air mixtures. These parameters seem to influence the transition from bubble to slug flow but not the transition from slug to annular flow. The results of the analysis incorporating the effects of the surface tension and inertia are in good agreement with the experimental data. Zhao & Rezkallah [7] present experimental data obtained on board of NASA KC-135 Reduced Gravity Research aircraft (a Boeing 707 derivative). The pressure losses by friction in the two-phase flows in forced convection are of the same order of magnitude as those measured on Earth. The result is explained by the fact that the flows are dominated by the effects of inertia. Reasonable agreement with various empirical models (homogeneous, Martiniell–Lockhart, Friedel) is obtained. The effects of gravity mainly result in modifications of structure (topology) of the flows rather than in modifications of hydrodynamic behavior of similar flow structures. However, it is important to note that the conclusions from studies of two-phase flows without phase change in microgravity are not necessarily applicable to channel flow boiling in microgravity when volumetric expansion related to phase change plays an important role. There are relatively few studies dedicated to the analysis of two-phase flows with phase change in microgravity.

Ohta [8] studied convective boiling of R113 in circular tubes during parabolic flights. The significance of this pioneering study is in the determination of void fraction variations in channel flows under microgravity, an issue which received relatively little attention in other publications. Flow visualization is carried out in a transparent vertical tube of the inner diameter of 8 mm for a range of values of the vapor quality. The vertical orientation allows the author to study the effect of the variations of gravity during the flight without transition to a different flow mode. Controlled pre-heating makes it possible to vary the type of the flow at the tube entry (e.g. annular flow, flow with bubbles and slugs). In order to visualize and heat simultaneously, a transparent resistive metal deposit is made by sputtering inside cylindrical Pyrex tubes. Photolithography is used to place thermistors of the location along the minichannel axis (m)

Greek symbols

\[ \alpha \quad \text{void fraction (–)} \]
\[ \chi \quad \text{vapor quality (–)} \]
\[ \Delta \quad \text{difference inlet minus outlet (–)} \]
\[ \theta \quad \text{density (kg m}^{-3}\text{)} \]

Lower and upper letters

\[ V \quad \text{vapor (–)} \]
\[ L \quad \text{liquid (–)} \]
\[ I \quad \text{inertial (–)} \]
\[ T \quad \text{total (–)} \]
\[ G \quad \text{gravitational (–)} \]
\[ F \quad \text{frictional (–)} \]

---

**Table 1**

<table>
<thead>
<tr>
<th>First author</th>
<th>Year</th>
<th>Fluid</th>
<th>Weightlessness tool</th>
<th>Boiling regime</th>
<th>HTC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serret [23]</td>
<td>2010</td>
<td>HFE-7100</td>
<td>PF (ESA)</td>
<td>Convective +</td>
<td>+</td>
</tr>
<tr>
<td>Luciani [17]</td>
<td>2008</td>
<td>HFE-7100</td>
<td>PF (ESA)</td>
<td>Convective +</td>
<td>+</td>
</tr>
</tbody>
</table>
heat transfer coefficient were often not as significant. It was concluded that for the annular mode with sufficiently weak heat flow not to generate nucleate boiling, the coefficient of exchange in microgravity is deteriorated because of the increased thickness of the liquid film formed on the wall. For high mass velocity and high vapor quality no significant effect of gravity level on heat transfer is detected.

The most recent studies are summarized in Table 1 in order to highlight the topics which are currently under investigation. Straub [9] analyzed the results obtained during the ‘SpaceLab IML-2’ mission in 1994. The objective of the mission was to carry out experiments on pool boiling in microgravity by using a hemispherical thermistor of 0.26 mm in diameter both for heating and for measuring the temperature. The author studied the influence of the subcooling of R11, which was the fluid used, on the heat exchange. The experiments were repeated on Earth after the mission. For high subcooling, the heat transfer coefficient is slightly lower than its value under terrestrial gravity. However, for subcooling ranging between 10 and 30 °C, the transfer worsens in microgravity to reach ~50% with 30 °C of subcooling. For values of subcooling lower than 10 °C the heat transfer coefficient becomes again almost identical to that under terrestrial gravity. The author notes that the power densities measured in µg or in 1 g reach 900 kW m−2. These power densities are approximately twice as high as the values obtained for experiments on a wire and ten times higher than those obtained on a planar surface. Moreover, the author concluded that the microgravity strongly influences the heat transfer only in the area of transition between nucleate boiling and film boiling.

The influence of the extent of the heated surface on pool boiling is the object of study by Henry & Kim [10]. The authors investigate boiling on a heater composed of 96 platinum resistance square heaters of size 0.27 mm × 0.27 mm. Each individual small heater can be activated independently. This setup allows the authors to obtain several heating configurations. The results are presented for the following cases: 9 heaters, resulting in a square heated area of 0.66 mm², 36 heaters and heated area of 2.62 mm², and finally of 96 heaters and heated area of 7.00 mm². Boiling was studied in hypergravity at 1.7 g ± 0.5 g and in microgravity at 0.01 g ± 0.025 g. The fluid used is FC-72 whose temperature of saturation is 56.7 °C at 1 atm. The heating system is controlled to ensure constant temperature. The authors can reach a given power with the heat flow transferred by boiling. They can thus easily determine the heat transfer coefficient. For the configuration of 9 heaters, there is a single bubble formed in both hyper- or microgravity, but its size is smaller for the case of microgravity. For the larger heated surfaces at several values of the superheat, there are also qualitative differences, with multiple bubbles observed under hypergravity for the conditions corresponding to single bubble formation under microgravity. The authors also conduct detailed investigations of the influence of the superheat on heat transfer during the formation and evacuation of bubbles under different levels of gravity.

Zhang et al. [11] study the critical heat flux (CHF) for boiling during flight campaigns on board of KC-135. They used a millimeter-length channel in a block of Polycarbonate (Lexan) covered with a heating copper sole. The observation of the flow structures is carried out with a high-speed camera. The authors analyze flow patterns for different values of mass flow rate and heat flux. The latter is typically close to the critical heat flux. In their conclusions, the authors highlight the absence of nucleation during microgravity and bubble coalescence which results in the formation of vapor plugs moving with the flow. The presence of long vapor filaments fluctuating and propagating along the walls is noted. The access to heating surface for the liquid is then more difficult because of the vapor films.

Kawamura et al. [12] study convective boiling of liquid nitrogen in microgravity by using JAMIC drop shaft. The liquid nitrogen was selected since many of its physical properties, such as saturation temperature, are close to those of hydrogen and oxygen. A gold transparent resistive deposit of 10 nm is used to initiate boiling in a Pyrex tube of interior diameter of 7 mm. The aim of the study is to observe the behavior of a cryogenic fluid in microgravity. The behavior of cryogenic fluids near saturation in microgravity is important for many space applications, especially the re-start of cryogenic engines in orbit. The dynamics of the fluid in conduits, the separation of the phases as well as boiling caused by solar heating are subject of many studies conducted by international research teams.

Zhao et al. [13] recently published a study based on an experimental campaign on board of a Chinese scientific satellite dedicated to pool boiling on a heated wire. The fluid used in this study (R113) is undercooled by 26 °C. Boiling is initiated by electrically heating a platinum wire of 60 mm in length and 30 µm in diameter. The resistivity of the platinum wire is used not only for heating but also to determine the average temperature of the wire. The authors highlight a slight improvement of the heat transfer for this situation of boiling compared to results obtained on Earth. Whereas the presence of gravity allows the evacuation of the vapor bubbles generated at the heating wire, the authors confirm that in spite of the presence of static bubbles, the average temperature of the wire is slightly higher than under conditions of normal gravity. This enables them to conclude that the heat transfer coefficient is slightly better; note that the wire is heating at constant electric power.

Despite the recent accumulation of experimental data on channel flow boiling under microgravity, development of mathematical models of such systems has been very limited. However, the closely related problem of isothermal two-phase flow in a channel have been well-understood for a wide range of channel sizes and discussed in detail e.g. in Fabre & Liné [14], Ajaev & Homsy [15], and Clanet et al. [16]. For practical applications, it is important to understand the connection between these models and the experiments on flow boiling in minichannels under microgravity conditions. Of particular interest is the issue of how to modify these isothermal models to match the conditions relevant to the situations when vapor bubble volumes do not remain constant as a result of phase change.

Similar measurement techniques have been used also to determine the void fraction to two-phase flow in ducts. Puli & Rajvanshi [24] use an image analysis technique for determination of void fraction in subcooled flow boiling of water in horizontal annulums at high pressures. Leandro et al. [25] use the pixel intensity in order to characterize the void fraction in a sudden transition from supercritical to subcritical flow.

The objectives of the present study are two-fold. First, we analyze experimentally observed flow patterns and frictional pressure drop data to explain the previously reported increase in the local heat transfer coefficient in minichannels under the conditions of reduced gravity [17,18]. Second, we use mathematical modeling to interpret and explain the experimental data on void fraction and frictional pressure loss in minichannels during flow boiling under reduced gravity.

2. Material and methods

2.1. Experimental set-up

The core of the experiment is inside a confinement box due to parabolic flight safety considerations. The experimental rack is divided into 4 areas: the confinement box, the material storage
zone below the confinement box, the visualization zone with computer 2, the loop control zone with computer 1. The entire fluid loop is inside the confinement box to avoid fluid leaks into the cabin. The heating system consists of a small cement rod of dimensions $16 \times 10 \times 70$ mm$^3$ with a heating wire of diameter of 0.4 mm. K-type thermocouples of diameter of 0.14 mm fabricated at our laboratory are used to measure the cement rod temperature at several locations in the minichannel under the heating surface.

The cooling system is realized using Peltier elements with heat sinks as shown in Fig. 1. The fluid flow is generated by a syringe pump (two-way, two fluid loops) to investigate flow boiling simultaneously in two channels at the same mass flow rate. The channels are identical and are heated in the same way. One channel is used for pressure and temperature measurements while the other channel is used for flow visualization. Thus, it is possible to simultaneously observe flow patterns and measure pressure loss and heat transfer coefficient. A 3-h procedure for degassing, warming up the confinement box, and preparing the experiment is required before the flight. The working temperature inside the box is 45 °C to reduce heat losses.

The fluid investigated is HFE-7100; its physical properties under the conditions of our experiment are listed in Table 2. This fluid has been chosen for its many advantages. It has low boiling temperature (54 °C at 820 mbar), low heat of vaporization (20 times less than water), is colorless, non-toxic, non-inflammable, non-explosive, and chemically compatible with typical materials used in experiments (aluminum, copper, Teflon, Polycarbonate). The channel cross-section is $6 \times 0.454$ mm$^2$, hydraulic diameter is 0.84 mm.

The capillary lengths of HFE-7100 under different gravity levels are listed in Table 3. The change from hyper-gravity to microgravity results in an increase of the capillary length by a factor of about 6. The bubble characteristic sizes are therefore bigger and thus the confinement effect is more significant. Note that the Bond number is far below one for microgravity and above one in hyper-gravity so the two gravity levels (microgravity and hyper-gravity) can be used to study the influence of gravity on the two-phase flow and heat transfer. The use of minichannels is important in a global frame of device size reduction. Using microgravity, it is possible to suppress the density differences between liquid and vapor and have capillary driven heat and mass transfers. The use of both minichannels and microgravity enables one to reach higher confinements. The change from terrestrial gravity to microgravity is equivalent to a reduction of hydraulic diameter by a factor of 4.5 without the pressure loss problem. On the ground, such experiments would require micro-channels of hydraulic diameter below 200 µm.

**Fig. 1.** Confinement box and experimental equipment to study flow boiling in two channels.
The channel is engraved in an Inconel thin plate \((2 \times 16 \times 70 \text{ mm}^3)\). A transparent polycarbonate plate is used to cover the channel while allowing for flow visualization. Two pre-heaters are used to warm the liquid up to \(2 \degree C\) below its saturation temperature. Thus, it is reasonable to assume that the fluid at the minichannel entrance is close to the saturation conditions. The pressure measurements are acquired at 133 Hz to be able to observe non-stationary flow. The fluid temperatures are measured at the same frequency. Gravity level is measured by an accelerometer. The flow visualization is performed using a Photron Ultima 1024 Fast-Cam, the videos are acquired at 1000 img/s with a shutter at 250 \(\mu\text{s}\) in 1024 \(\times\) 512 pixels.

2.2. Void fraction measurement

The void fraction is determined assuming that there is a narrow gap between the heating plate and the top cover so that the geometry is essentially two-dimensional. Then the void fraction is calculated along the minichannel from the ratio between the number of vapor pixels to the total number of pixels across the minichannel.

In practice, to determine the void fraction a program was developed using Matlab. The main difficulty in the treatment of multiphase flow videos was due to the substantial similarity between the shapes of liquid and vapor regions. So, the outlines of the bubbles must be detected accurately, since the external and internal regions often have the same features. Also, the acquisition frame rate should be high enough to capture the displacement of each bubble between two subsequent images. Small deviations of the channel from the vertical orientation also have to be taken into account during image treatment. Fig. 2 illustrates the use of data from the image to determine the inclination of the tube, determined from the linear fit seen in Fig. 2(b).

In order to improve image quality, it is important to eliminate patterns which are present in every image and are due to solid surface roughness, defects, and other factors not related to the flow. To achieve this, an average image of a video set is obtained and then subtracted from each individual image in the set. A typical result is shown in Fig. 3(a). With the adjusted images, we begin the most difficult step of the image treatment: defining and applying the threshold for automatic recognition of the gas bubble. For this, the images were first divided into nine regions, shown in Fig. 3(b), in which we identified a recurrent behavior throughout the flow. For example, the lower regions of the tube had smaller bubbles with well defined contours, allowing the application of a less sensitive filter. However, the bubbles in the regions near the tube wall were so small that they could be confused with noise, which prevented the application of a single filter.

At the next step, the contours were treated separately depending on the area they enclose. After the treatment, the contours that have been identified as bubbles were copied to a new image, see Fig. 3(c). The small contours corresponding to the smaller bubbles were directly copied, without prior treatment, because they were easily identified. The contours of intermediate dimensions were treated with a process of dilation followed by erosion. For the contours of larger size, the same procedure has been applied, followed by a reduction in the thickness of the contours. The latter step was needed to ensure that the distances between the larger and smaller bubbles are precisely known, so that small liquid regions between them were not identified incorrectly as vapor. The last step consists of identifying the number of pixels of vapor in each line of each image and applying this entire process for all images of the video. Calculating the average percentage of vapor for each line, we obtain a good approximation for the profile of the void fraction. To reduce the influence of the bubbles that were not fully resolved, as indicated by breaks in their outlines, the images were...
3. Experimental results

During a flight, the experiments are conducted with a constant heat flux supplied to the channel. Several values of the heat flux are investigated, from 15 to 55 kW m$^{-2}$. The mass flow rate values are from 30 to 248 kg s$^{-1}$ m$^{-2}$. Due to the short time interval between two parabolas (120 s), the mass flow rate decrease has to be small so that there is enough time to reach a new steady-state configuration. The experiments are performed twice for the same heat flux and the same mass flow rate to realize two movies: one during hypergravity and one during microgravity. The channel orientations both in 1g and 1.8g are vertical to investigate the influence of gravity along the main flow axis. Reproducibility tests have been performed before flight campaigns at normal gravity. Heat losses are estimated considering natural convection and radiation from the cement. The locations of temperature and pressure measurements are detailed in Luciani et al. [17].

3.1. Minichannel pressure loss

Several pressure sensors are located in the loop to access the local pressure variation in the channel and the total channel pressure loss. For both channels, it is possible to measure the total channel pressure loss. An absolute pressure sensor measures the tank pressure to obtain the average saturation loop temperature. The experiments are performed at a constant heat flux. Let us first discuss the results obtained at the heat flux of 32 kW m$^{-2}$. The highest liquid inlet mass velocity considered in this subsection is 138 kg s$^{-1}$ m$^{-2}$, corresponding to the inlet liquid Reynolds number of 257. The range of Reynolds numbers investigated in our experiments corresponds to laminar flow. Gravity level evolution during a parabola is illustrated in Fig. 4. At normal gravity (1g) the pressure loss is constant and equal to 2770 Pa. The hypergravity period begins and the pressure loss increases to 4070 Pa, then falls down to 1010 Pa during the microgravity period. The second hypergravity period seen in Fig. 4 is not considered.

3.2. Influence of gravity level on the pressure loss

The same general trends in pressure loss variations are obtained for all experiments. In Fig. 5, we show total pressure loss for microgravity, normal gravity and hypergravity for the heat flux value of 15 kW m$^{-2}$. The total pressure loss varies linearly as a function of the inlet liquid Reynolds. This is not surprising since the flow is laminar for this range of Reynolds numbers and can be considered two-phase everywhere in the channel (recall that liquid enters the channel at saturation temperature). We also observe that the pressure loss decreases as the gravity level is decreased.

The effect of gravity level on the pressure loss is twofold. First, there is direct influence through the gravitational pressure loss, expressed in terms of the void fraction $\alpha$ using simple formula from hydrostatics,

$$\Delta P_G = \int_0^L g(z)dz, \quad \Delta P_P = \frac{\int_0^L \phi(z)g(z)dz}{\int_0^L \phi(z)dz}.$$  

Second, there is less direct influence due to changes in the overall flow structure (bubble sizes and growth rates, coalescence rates, etc.) with gravity level. In order to better understand such influence, it is useful to re-plot the experimental results with the term $\Delta P_G$ subtracted from the total pressure loss, as is done in Fig. 6. The pressure drops redefined this way are still significantly different for different gravity levels, clearly indicating that the effect of gravity is not limited to the hydrostatic contribution.

To clarify the physical meaning of the quantity plotted in Fig. 6, we note that after the hydrostatic effects are subtracted, the pressure drop is in general determined by the combination of frictional and inertial pressure loss. The latter can be estimated from

$$\Delta P_I = \frac{\mu_L \varphi_{L}}{\varphi_{L} (S(L) - 1)} \quad \text{(3)}$$

$$S(z) = \frac{u_G(z)}{u_L(z)} \quad \text{(4)}$$

$$S(z) = \frac{\varphi_{L}}{\varphi_{L} (1 - \chi(z))} \quad \text{(5)}$$
Thus, we conclude that the result shown in Fig. 6 basically represents the frictional pressure loss in our two-phase flow, i.e.

\[ \Delta P_F = \Delta P_T - \Delta P_G. \]  

(6)

According to Fig. 6, the frictional pressure loss increases linearly with the Reynolds number and increases with gravity level. In hypergravity, the frictional pressure drop is about 1.3 of the value corresponding to normal gravity, while it is half of that value during experiments conducted in microgravity. Comparing the slopes of the lines in Fig. 6 suggests that the frictional pressure drop increases linearly with the gravity level, but more data at different gravity levels should be obtained to confirm this.

Let us now discuss the results for pressure loss under microgravity in more detail. First, we observe that the two-phase pressure drop recorded in experiments is significantly higher than the single-phase liquid flow pressure loss. The latter can be estimated from the expression discussed in detail in Fuerstman et al. [20] and written in the notation of the present article as

\[ \Delta P = \frac{a \mu L U_m}{\rho_1 H^2}, \quad a = 12 \left[ 1 - \frac{192H}{\pi^2 \tanh \frac{\pi W}{2H}} \right]^{-1}. \]  

(7)

For the mass velocity of \( U_m = 138 \text{ kg m}^{-2} \text{ s}^{-1} \), the single-phase pressure drop in microgravity is 166 Pa, while the measured value for the two-phase flow is approximately 1200 Pa. One may argue that in the regime when the void fraction is very high everywhere along the channel, a model of single-phase flow of vapor can give accurate predictions. However, even though estimates based on single-phase flow of vapor are much closer to the experimentally measured values of the frictional pressure loss in microgravity, they do not explain the dependence of pressure loss on gravity. In fact, in

---

**Fig. 4.** Typical sequence of a parabola during a parabolic flight.

**Fig. 5.** Total channel pressure loss as a function of the inlet liquid Reynolds number for \( Q_m = 15 \text{ kW m}^{-2} \).

**Fig. 6.** Total pressure loss with gravitational pressure loss subtracted out, plotted as a function of the inlet liquid Reynolds number.
single-phase viscous flow models the pressure losses should be identical when the hydrostatic pressure loss is subtracted out, which is in contradiction with the experimental results shown in Fig. 6. Thus, understanding the structure of the two-phase flow is essential for explaining the data on pressure loss in microgravity.

Different approaches to modeling of two-phase flows in rectangular channels have been proposed in the literature depending on the characteristic bubble sizes. If bubbles are small compared to the channel cross-sectional size and at low concentration, the flow can be modeled as single-phase flow with small corrections to density and viscosity due to the presence of the bubbles. However, such approach does not lead to predictions of a dramatic increase of the pressure drop compared to single-phase flow without bubbles. For bubbles which almost completely fill the cross-section, a key contribution to the pressure loss is due to pressure drops at the front and back caps [15,20]. If our flow is modeled by a sequence of such bubbles, then a moderate increase in the pressure drop compared to single-phase flow can be obtained, but the explanations for the significant increase in the pressure loss seen in experiments and its dependence on the gravity level are still lacking. An alternative approach is to consider bubbles of intermediate dimensions which are growing at nucleation sites, partially filling the channel cross-section and thus acting as obstacles to the liquid flow. The effect of such bubbles is to effectively reduce the cross-section for the flow (since the actual mass loss due to phase change is not significant due to the large ratio of the densities). We believe that this situation provides a better description of the experimental observation than the other models discussed above. For high void fraction values, the pressure loss increase by a factor of 5 or 6 can be easily explained. Furthermore, increase in void fraction in microgravity, discussed in more detail in the following section, provides an explanation for the differences between pressure losses in hypergravity and microgravity.

4. Void fraction variation

4.1. Influence of the flow regime

The void fraction profiles along the minichannel are shown in Fig. 7 for different mass velocities at constant heat flux provided to the minichannel under hypergravity (see Fig. 7). The mass velocities are in the range between 147 and 248 kg m\(^{-2}\) s\(^{-1}\) and the heat flux is constant at 45 kW m\(^{-2}\). For all mass velocities, low void fractions are observed near the minichannel entrance and the void fraction tends to increase in the direction of the flow along the minichannel. For higher mass velocities, 217 kg m\(^{-2}\) s\(^{-1}\) and above, the void fraction increase is approximately linear, associated with bubbly flow. At lower velocities, the void fraction increase is no longer linear; in fact, the curves start to flatten at about 17 mm from the channel entrance for \(U_m = 186 \text{ kg m}^{-2} \text{s}^{-1}\) and at \(z = 15 \text{ mm}\) for \(147 \text{ kg m}^{-2} \text{s}^{-1}\). The part of the channel which corresponds to nearly constant void fraction is typically characterized by high coalescence rate, as seen in the videos of the two-phase flows.

4.2. Influence of the gravity level

Experiments were performed for the same experimental conditions twice to record the flow patterns under hypergravity conditions and microgravity conditions. Let us first consider the experimental data at relatively low heat flux of \(Q_w = 20 \text{ kW m}^{-2}\)
shown in Fig. 8, which indicates higher void fraction under reduced gravity compared to hypergravity at the same locations in the minichannel. Both variations are approximately linear along the minichannel.

The changes in the volume fraction variation under microgravity can be understood using the following simple considerations. The variation of the void fraction along the minichannel depends on two factors: the growth rate of bubbles by evaporation and the rate at which the bubbles are advected by the flow. The bubbles near the entrance to the channel are expected to be small (since the fluid is single-phase as it enters the channel) and therefore their growth is governed mostly by inertia effects. At this stage, the key factor in bubble growth is the value of the pressure built up inside as a result of evaporation, so the growth rate can be assumed constant in time and independent of the thermal field around the bubble, meaning that the characteristic bubble size $R_b$ is

$$R_b = A_1 t.$$  \hspace{1cm} (8)

As the bubble travels along the channel at a characteristic velocity $U_b$, the void fraction should increase according to the bubble size at a location $z$, meaning that in the region near the channel entrance the characteristic bubble sizes are determined by $R_b = A_2 z/U_b$ and therefore the void fraction is linear in $z$ (in fact, proportional to $z/U_b$). Such linear regime is indeed observed in Fig. 8 except near the end of the channel. We note that in reality there is a size distribution of bubbles due to some degree of randomness in the initial nucleation locations, so all arguments in the present section should be understood in the average sense.

The bubble velocity, $U_b$, under normal or hypergravity can be written as a combination of the effects of buoyancy and the external pressure gradient [14].

---

**Fig. 10.** Flow patterns sequence (one image every 10 ms presented) in a 0.84 mm diameter minichannel during hypergravity and microgravity (see movie provided online) for $Q_w = 32 \text{ kW m}^{-2}$ and $Q_m = 71.6 \text{ kg m}^{-2} \text{s}^{-1}$.
where $U_b$ is the average flow velocity at the channel entrance, $C$ is a coefficient which depends on channel geometry, and $V$ is the bubble rise velocity under the conditions when liquid is at rest. For rectangular channels, the coefficient $C$ is close to unity for a range of conditions [20,21], while the velocity $V$ according to the model of Clanet et al. [16], applied to the conditions of hypergravity, is $V = \sqrt{\frac{1.88gP}{8\pi}}$.

It is important to note that the above considerations are based on the assumption that no bubbles are present near the channel entrance and that the effects of bubble coalescence and finite width of the channel are not significant. Furthermore, the model also neglects the thermal effects. If the latter dominate bubble growth, its radius should grow with time according to $t$, resulting in the square-root-type dependence of the void fraction on the spatial coordinate. This is in qualitative agreement with the fact that void fraction curves at lower mass velocities tend to be more convex, as seen e.g. in Fig. 7. We do not attempt more quantitative comparison here since the flow structure becomes too complex (due to bubble–bubble and bubble–wall interaction) for our simplified models to be quantitatively accurate under parameters corresponding to the data in Fig. 7.

For higher heat flux provided to the minichannel, the flow pattern with gravity is still qualitatively similar to the ones seen in Fig. 8, while in reduced gravity the flow is dominated by long vapor plugs, as seen in Fig. 9 (Movie provided online). Void fraction data for hypergravity is characterized by two regimes, which can be qualitatively described by the two different mechanisms of bubble growth, as discussed above. The nearly linear growth is seen in the void fraction data in Fig. 9 at $z$ up to $\sim 20$ mm, followed by convex curve at higher values of $z$. The void fraction curve under microgravity is more complicated due to formation and interaction of long vapor plugs.

### 4.3. Film formation in reduced gravity

The visualization minichannel is used to analyze the two-phase flow structures directly from fast video recordings. In Fig. 10, we compare two sequences of snapshots from the videos at a given heat flux and mass flow rate. Differences in the bubble sizes for different levels of gravity are clearly seen. In Fig. 10, the exit vapor quality in both cases is 0.2. The hypergravity frame at the bottom and the middle of the channel shows a lot of small bubbles, whereas for the microgravity frame large vapor plugs are observed. Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.applthermaleng.2012.11.017.

The bubble sizes observed during the hypergravity period can be explained by the force balance on the bubble. The bubble departure from the nucleation sites is also influenced by gravity. The heating surface is vertical; the buoyancy force tends to detach the bubble from its nucleation site whereas the capillary force tends to maintain the bubble shape. The two forces are described using the Bond number which compares the gravitational force to the surface tension force. For both cases, the forced convection due to the constant mass flow rate injected will detach the bubble. However, without gravity, a bubble can grow on the vertical surface and become significantly larger compared to the situation with gravity. Also, an increase in the number of bubbles induces greater frictional pressure loss.

The heat transfer enhancement under reduced gravity everywhere along the minichannel and especially at the channel entrance has been observed previously by Luciani et al. [17]. While close to the minichannel entrance, this result can be explained by the difference in flow patterns and void fraction, the heat transfer enhancement away from the entrance, where the flow patterns turn out to be rather similar, is more difficult to explain. We propose the following mechanism. As a bubble moves through the channel, it is separated from the channel wall by a thin film, as sketched in Fig. 11. This film is essentially a trailing film behind the frontal part of the bubble, formed by the Landau–Levich–Brentherton type mechanism discussed in detail in e.g. Ref. [15]. The typical thickness of this film increases with bubble velocity. In microgravity, buoyancy is negligible and bubbles move slower (as is also seen in the movie provided online), resulting in reduction of the film thickness. Note that the presence of the gravity also modifies the structure of the transition region between the front of the bubble and the film on the wall, but for the Bond numbers of interest here, this modification does not have a dramatic effect on film thickness, which mostly is defined by the value of the bubble speed. The thin film formed on the wall makes a significant contribution to the heat exchange between the wall and the two-phase flow since for fixed temperature drop across the film, the heat flux is inversely proportional to film thickness. Thus, the flux...
across the film is higher as its thickness is decreased, so the heat removal from the hot surface of the channel is more efficient.

5. Conclusions

The influence of gravity level on flow boiling has been investigated during two parabolic flights campaigns. We found that in microgravity, the frictional pressure loss is about a half of the value at normal gravity while during hypergravity (1.8g) it is 1.3 times higher than at normal gravity. The increase in the pressure drop has been explained by the decrease of the void fraction with gravity level since lower void fraction leads to increase of the effective cross-section for the liquid flow.

The flow pattern analysis shows that the two-phase flow is typically characterized by relatively small bubbles in hypergravity while big slugs tend to form under conditions of microgravity. The bubble departure diameters are strongly influenced by gravity due to the buoyancy effects, leading to the increase of the frictional pressure loss with gravity. Void fraction changes along the channel for different gravity levels have been explained based on the mathematical models predicting the velocity of bubbles traveling through rectangular channels under different conditions. In particular, our model gives accurate predictions of the change of slope of the void fraction curve with gravity in the regime when the increase of the model gives accurate predictions of the change of slope of the void fraction curve with gravity in the regime when the increase of the pressure drop has been explained by the decrease of the void fraction with gravity level since lower void fraction leads to increase of the effective cross-section for the liquid flow.

The local heat transfer enhancement found in Luciani et al. [17] has been explained in the present study by analyzing thin films separating vapor plugs from the wall of the channel. The film thickness is expected to be lower in microgravity, resulting in higher values of the heat flux even when the flow patterns are similar.

Acknowledgements

We would like to thank the European Space Agency for their financial assistance and the parabolic flights campaigns realized at Bordeaux, Merignac, France. Also, we would like to thank Nove-space for their assistance during the campaign. The authors gratefully acknowledge the help and the fruitful discussions with J. Duplat and R. Pizarro on the void fraction determination.

References


