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Quenching experiments inside 6.0 mm tube at reduced gravity

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ABSTRACT

This paper addresses the experimental results of quenching in tubes under microgravity conditions. The objective of the experiment is to obtain quantitative data and observations of the rewetting phenomenon under low gravity level and compare results with the equivalent terrestrial gravity ones. Test tube is made of Pyrex with 6.0 mm in diameter. Tests are performed with FC-72, a fluorinert liquid, flowing inside a vertical test section and upward liquid flow. Measurements included outer wall temperatures along the flow channel, inlet and outlet fluid temperatures, pressure and mass flow-rate. The results show a significant decrease in the quenching velocity at reduced gravity, while the rewetting temperature does not look to be affected by gravity level. The observed flow patterns are inverted annular flow and bubbly flow. The analyses are completed with a detailed high speed video images at normal gravity. These tests reveal the influence of mass flow-rate on the structure of vapour–liquid configuration during the inverted annular flow.

1. Introduction

Flow boiling heat transfer is the most efficient way to achieve the possible high heat transfer demand from future space applications. This efficient heat transfer regime might be employed in a wide range of microgravity systems such as satellites for communications, thermal management of the International Space Station, cooling of electronic devices subjected to high thermal load (i.e., high heat flux), thermal transport, cooling of nuclear space reactors, etc. In order to develop and design these thermal systems for space applications (in particular heat exchangers), it is necessary to achieve a detailed understanding of all flow boiling aspects under low gravity conditions. One relevant aspect related to flow boiling for space applications is quenching, which is an important process which occurs during the transfer of liquid oxygen and hydrogen, typical rocket fuels.

Basically speaking, quenching is encountered when a cold liquid flows on a dry and hot surface and the surface temperature is sufficiently higher than a certain limit. This limit is called rewetting temperature, the highest temperature at which direct contact between the cold liquid and the hot surface is possible, i.e., the limit temperature which allows the liquid to wet the solid surface. Under these conditions, heat is removed from the hot surface through various modes of heat transfer to the coolant: boiling, convection, radiation, and conduction through the channel wall. Wall temperature is affected by all these heat transfer mechanisms and changes with time. When the wall temperature falls down the rewetting limit, the liquid coolant comes in contact with the hot surface, rewetting it and the heat transfer is mainly between the liquid and the wall, besides axial conduction in the wall. The extreme portion of the surface rewetted by the coolant is called quench front.

The complex heat transfer mechanisms occurring during quenching phenomena are still far from being understood at normal gravity conditions. At reduced gravity the situation is even worst, also because of the reduced amount of available experimental data [1–4].

Antar and Collins [1] obtained flow pattern visualization and wall temperature measurements during quenching of a hot tube aboard the NASA KC-135 aircraft, using saturated liquid nitrogen. Two test sections are used, 10.5 mm I.D. and 600 mm long, and 4.32 mm I.D. and 700 mm long, respectively. Authors describe a new two-phase flow pattern at reduced gravity indicated as *filamentary flow*. The filamentary flow is a sort of inverted annular flow characterised by a long liquid filament flowing in the centre of the channel and surrounded by vapour. The filaments have a diameter of approximately one third of the pipe diameter. Rewetting time is found to be longer than that at normal gravity (lower rewetting velocity), thus gravity affecting the total duration of the quenching process.

Westbye et al. [2] performed quenching experiments of a hot tube at microgravity aboard the NASA KC-135 aircraft, using subcooled R113 in a horizontal stainless steel tube, 11.3 mm I.D. and 914 mm in length. Rewetting temperature at low gravity is 15–25 °C lower than at normal gravity. Heat transfer coefficients during film boiling at low gravity are lower (up to 50%) than those at normal gravity. Therefore, the total duration of the quenching process is found to be significantly longer at microgravity (lower

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Nomenclature

D	tube diameter (m)
G	mass flux (kg/m^{2}s)
G	gravitational acceleration (m/s^2)
g_o	gravitational acceleration at earth (m/s^2)
p	pressure (MPa)
t	time (s)
T	temperature (°C)
u	velocity (m/s)

Subscripts

Rew	pertains to the rewetting condition
in	pertains to the inlet conditions
wall	pertains to the channel wall

rewetting velocity). The observed flow pattern at μ–g is inverted annular flow and dispersed flow, with a thicker vapour film thickness in inverted annular flow.

Adham-Khodaparast et al. [3] conducted transient quenching experiments on a hot flat surface under microgravity conditions aboard the NASA KC-135 aircraft for an inlet flow of Freon-113 with 20° C subcooling. They have found that: (i) initial rewetting of the hot surface occurs for surface superheats well above the expected rewetting superheats for Freon-113; (ii) wall superheat at the onset of rewetting increases with mass velocity, inlet subcooling and the gravity level; (iii) heat transfer coefficient during film boiling is considerably reduced in microgravity due to the thickening of the vapor film; (iv) maximum heat flux during rewetting increases with an increase in mass velocity, inlet subcooling and gravity.

Kawaji et al. [4] carried out quenching experiments of a hot tube at microgravity aboard the NASA KC-135 aircraft, using R113 with inlet subcooled conditions. The test section is a quartz tube, externally heated by a nichrome heating tape wound around the tube and connected to an AC power source, 14.0 mm I.D. and 1.2 m long. The two-phase flow pattern encountered in a transient quenching process in microgravity is different from those found under 1-g conditions, and, as a consequence, the heat transfer rate is substantially reduced.

Antar and Collins [5] investigated flow patterns and heat transfer during a quenching process using a quartz tube with an ID of 4.32 mm for the visual recording of the flow pattern and measurement of the outer wall temperature, respectively. This experiment did not report the heat transfer characteristics of the quenching process, such as the heat flux and heat transfer coefficient. Besides, terrestrial and microgravity experiments were generally not conducted under same mass velocity conditions.

Kawanami et al. [6] conducted an experiment at JAMIC (drop shaft, 10 s of microgravity) using LN_2 as a test fluid, and a transparent heated tube for observing fluid behavior and measuring heat transfer during tube quenching. Experiments were performed in a low mass velocity region (100–300 kg/m^{2}s) that is easily influenced by gravity. They have found that: (1) the heat transfer and quench front velocity increase in microgravity; (2) the heat transfer and quench front velocity under microgravity conditions increase up to 20% from those under 1 g, and the difference in the heat transfer characteristics under 1 g and μg decreases with increasing mass velocity. It is concluded from these results that the increase in the heat transfer under microgravity conditions is caused by the increase in the quench front velocity.

Considering the scarcity of available data and the interest for the space industries in this phenomenon, the present paper is focused on the understanding of the flow pattern and thermal characteristics during quenching of pipes with subcooled coolant at reduced gravity. The study intends to clarify the effect of mass flow-rate on quenching at reduced gravity. The present paper reports on the results carried out with the largest tube diameter planned for the research, i.e., the 6.0 mm pipe.

2. Experimental facility

The experiments at reduced gravity were conducted onboard of a modified Airbus A-300, called Zero-G, maintained by Novespace, which, among others, is used by ESA, the European Space Agency, for parabolic flight campaigns, where a period of reduced gravity of 20–22 s is achieved. During each parabola, lasting about 60 s, three gravity level are reached: hypergravity (1.5–1.8 g) during the first 20 s, microgravity (0.01 g) during the central 20 s, and again hypergravity during the last 20 s, before reaching levelled horizontal flight for a further parabola. A total of 30 parabolas each day are performed for a three-days campaign.

The experimental facility, schematised in Fig. 1, is named MICROBO (MICROgravity BOiling). It consists of a gear pump (G_{max} = 500 ml/min), a filter, a flow-meter, an electric pre-heater, the test section (where boiling phenomena occur), a condenser, a bellows, and a tank for the storage of the process fluid (FC-72). The test section, shown in details in Fig. 2, is made of a Pyrex tube, with an inner diameter of 6.0 mm, and for these tests is vertically

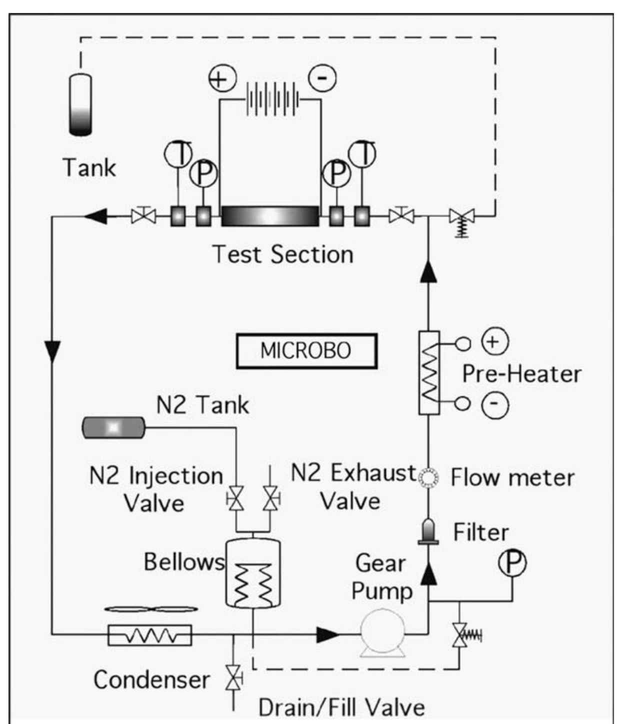

Fig. 1. Schematic of the experimental facility.

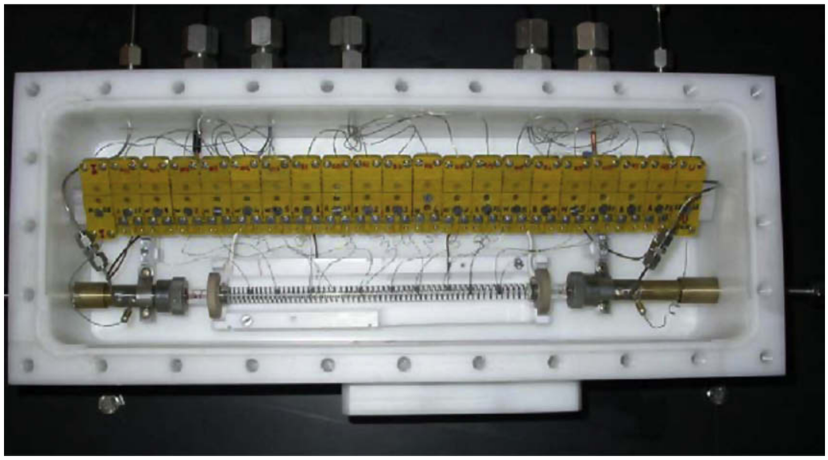

Fig. 2. Test section in the ERTACEL® confinement box.

oriented with upward flow (flow direction is always upward, though this makes sense only for terrestrial gravity tests). A metallic tape is coiled and wrapped on the outer surface of the Pyrex tubes in order to allow the tube heating (by Joule effect through the metallic tape) as well as flow visualization. Flow pattern visualization is performed with an ultra rapid shutter video camera on a digital video recorder with a frequency of 50 fps. The movies are taken near the exit section of the flow channel.

The wall temperature is measured by a set of ten thermocouples attached to the outer tube wall using an epoxy resin. Thermocouples are distributed at a distance of about 13 cm, starting from the inlet of the test tube.

The test section is confined in a special box made of ERTACEL® to avoid any leakage in the cabin in case of its break. Air contained inside the narrow space between the test section and the box walls (made of insulating material) soon reaches the temperature of the test section, thus reducing heat losses. Besides, during microgravity conditions natural convection is totally inhibited.

The working fluid is FC-72, perfluorohexane C_6F_{14}, a fluorinert liquid manufactured by 3M, used in electronic cooling and widely used for experiments of boiling on parabolic flights, and its principal physical properties are indicated in Table 1. Picture in Fig. 3 shows the experimental facility in flight configuration inside the cabin of the A300 Zero-G.

Table 1
Principal physical properties of FC-72.

Pressure	0.1013 MPa
Temperature	55.7 °C
Liquid density	1605 kg/m^3
Vapour density	13.33 kg/m^3
Heat of vaporization	95.7 kJ/kg
Liquid thermal conductivity	54.1×10^{-3} W/mK
Vapour thermal conductivity	12.9×10^{-3} W/mK
Liquid viscosity	0.44×10^{-3} Pa s
Vapour viscosity	12.02×10^{-6} Pa s
Liquid kinematic viscosity	0.28×10^{-3} m^2/s
Vapour kinematic viscosity	0.90×10^{-6} m^2/s
Liquid isobaric specific heat	1101 J/kgK
Vapour isobaric specific heat	894 J/kgK
Surface tension	7.90×10^{-3} N/m
Liquid expansion coefficient	1.30×10^{-8} 1/K
Liquid thermal diffusivity	3.06×10^{-8} m^2/s
Vapour thermal diffusivity	1.1×10^{-6} m^2/s
Liquid Prandtl number	9.0
Vapour Prandtl number	0.83

Fig. 3. MICROBO facility in flight configuration.

Table 2
Test matrix for the parabolic flight campaign.

D (mm)	6.0
G (kg/m^{2}s)	194, 278, 380
$\Delta T_{sub,in}$ (K)	−25
T_w (°C)	160, 190, 250
p (bar)	1.8

3. Experimental results

The test matrix of the experimental campaign, carried out in December 2004, has been carried out with reference to thermal hydraulic conditions as reported in Table 2. It should be noted that, although liquid subcooling at the quench front is an important parameter controlling the flow pattern and heat transfer above the quench front, the liquid subcooling at the inlet of the test section has been kept constant for all tests carried out in the experiment, nd equal to 25 K. The influence of liquid subcooling will be tested in further experiments.

Typically, the observed flow patterns during quenching experiments, with vertical hot tubes and subcooled liquids, are represented in Fig. 4. Two different types of flow pattern can be observed: inverted annular flow and bubbly flow. Inverted annular flow occurs when the heat transfer regime is of the film boiling type and the wall temperature is higher than the rewetting temperature, i.e., before the wall quenching. Bubbly flow occurs when

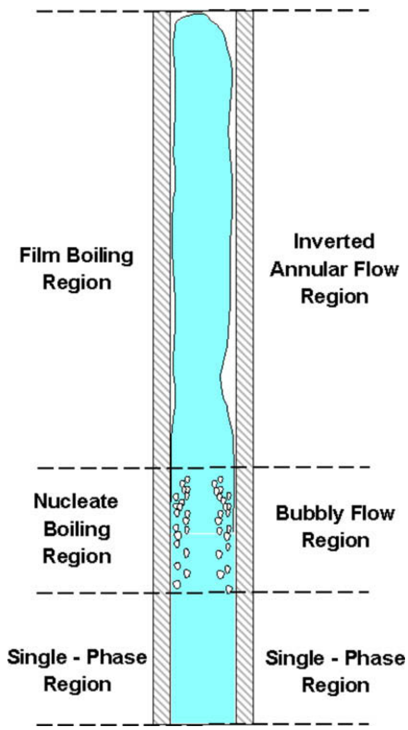

Fig. 4. Heat transfer regimes and flow patterns during quenching in a vertical hot tube.

the wall temperature drops under the rewetting limit and the liquid comes in contact with the hot surface, thus promoting bubble nucleation on the tube surface (nucleate boiling regime).

The typical quenching test is carried out first heating the test section, without any liquid flow-rate, during the hypergravity phase of the parabola (about the first 22 s of the aircraft pulling up). The electrical power during the drying period is selected in order to obtain the desired maximum wall temperature approximately at the end of the hypergravity phase. Once the wall temperature reaches the fixed temperature, the liquid flow-rate is injected into the test section thus starting the rewetting process. This typically starts as close as possible to the beginning of the microgravity period. Simultaneously, the thermal power is switched off along with the flow-rate injection.

Fig. 5 shows a plot of typical results of transient wall temperatures, for all the 10 thermocouples, during quenching experiments, for a generic parabola. In the graph the left vertical axis indicates the wall temperature, the right vertical axis indicates the acceleration level (as referred to the terrestrial gravity and normal to the floor of the aircraft), and the horizontal axis indicates time in seconds. The graph in the figure shows the dry-out period, during the hypergravity portion of the parabola, where the wall temperatures increase, which lasts up to few seconds after the beginning of the low gravity phase.

After the parabola, the test tube is heated (and dried) again in order to restore the required conditions for the next parabola and the tube wall temperature increases again to the prefixed value. The maximum wall temperature reached was 250 °C.

The plot in Fig. 5 shows that the highest temperatures are reached at the end of the test section (top) far from the inlet of the liquid: wall thermocouple T_{w1} is the more distant from the coolant inlet (bottom of the test section), while T_{w10} is the closest to the fluid inlet (top of the test section). Of course quenching will occur first close to fluid inlet and then propagate towards the bottom of the channel.

At the beginning of the quenching experiments, when the liquid is injected in the hot tube, only a stream of vapour is in contact with the channel wall, as the wall temperature is above the rewetting value. Vapour heat transfer is not very effective but, as the thermal power is switched off, a first reduction if the wall temperature is observed, after the peak value. In this phase, the heat transfer regime is governed by film boiling, and the liquid stream cannot get in touch with the hot wall due to its high temperature. When the wall temperature is reduced to the rewetting temperature, the liquid is then able to come into direct contact with the channel walls and nucleate boiling occurs. At this time the heat transfer rate from the hot wall to the liquid is significantly increased and a rapid variation in the wall temperature slope can be observed.

According to Westbye et al. [2], Chen et al. [7], Kim and Lee [8], and Barnea et al. [9], the rewetting temperature is defined as the apparent rewetting temperature obtained by drawing the tangents to the transient temperature curves in the regions where the significant change of the curve slope occurs, as schematically drawn in Fig. 6. In this figure, the rewetting temperature, T_{rew}, and rewetting time, t_{rew}, are plotted, as an example, with reference to the thermocouple T_{w3} (dotted line).

The point of intersection of the two tangents identifies the apparent rewetting temperature and the rewetting time along the tube axial distance, where the quench front arrives. In particular, the apparent rewetting temperature is identified by the intersection between the horizontal line, drawn from the intersection of the two tangents, and the temperature curve. The rewetting time is defined on the horizontal axis of the graph. This procedure

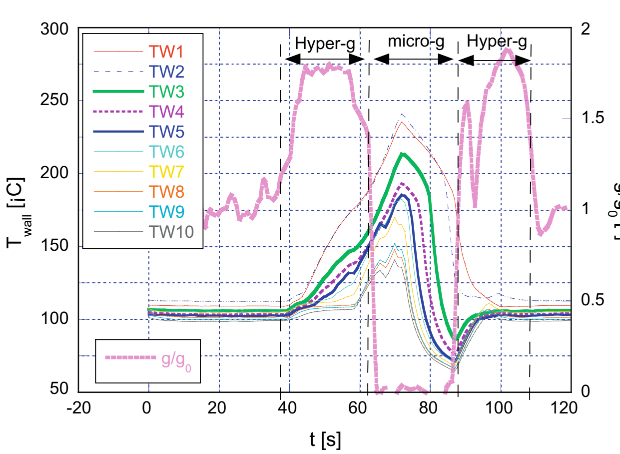

Fig. 5. Typical wall temperature and gravity level versus time traces for one generic parabola.

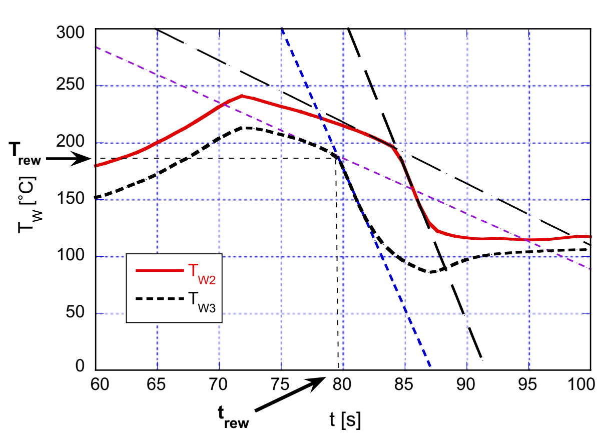

Fig. 6. Method for the determination of the rewetting temperature and time; values indicated on the axes refer to the dotted line wall temperature.

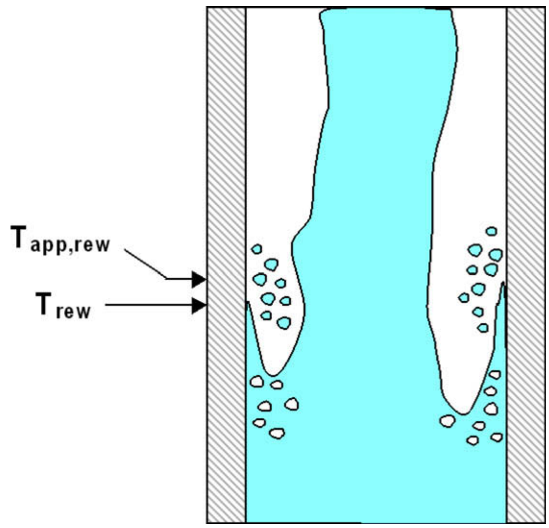

Fig. 7. Schematic of the flow pattern at the quench front (rewetting process).

is used for all readings of thermocouples which exhibit the characteristic significant change in their slope. Formally, and more theoretically, rewetting temperature, according to Barnea et al. [9], is defined as the temperature of the surface at which a triple interface, vapour–liquid–solid, is formed. This temperature is very difficult to be obtained from measurements on the outer surface of the test tube.

The relationship between the apparent rewetting temperature and rewetting temperature with the flow pattern during the rewetting process is represented schematically in Fig. 7, showing the complex vapour–liquid structures at the quench front according to the observations of Barnea et al. [9]. The authors observed the vapour film extended upstream the rewetting front and occasionally some liquid droplets cooled the dry surface downstream the liquid front. According to the previous definitions, apparent rewetting temperature, which is higher than the rewetting temperature, is the wall temperature recorded upstream the rewetting, or quenching, front. Although this consideration is strictly valid for terrestrial tests, we just established the reference conditions for the evaluation if the quenching conditions.

In the present paper, the apparent rewetting temperature will be referred to as the rewetting temperature. The rewetting (or quenching) front velocity is defined as the velocity of the quench front propagation along the tube when the liquid is injected in the dried out channel, and is the governing parameter of the process. The rewetting front velocity is calculated measuring the time

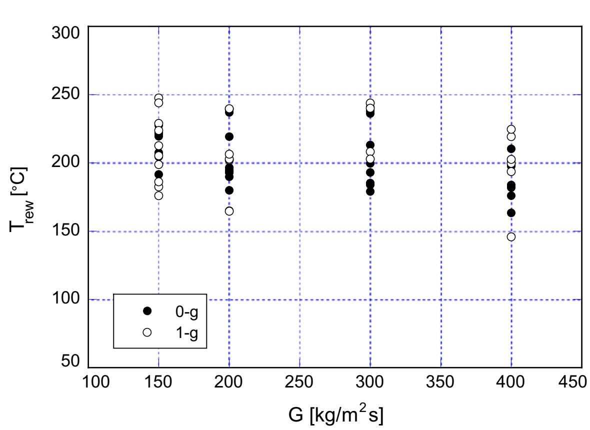

Fig. 8. Rewetting temperature versus mass flux for 1-g (empty triangles) and 0-g (full circles).

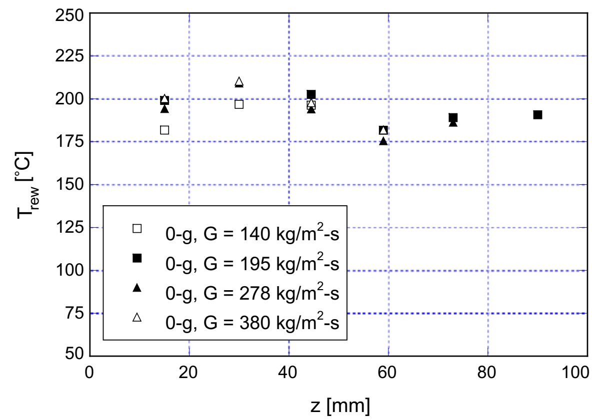

Fig. 9. Rewetting temperature versus axial location for 0-g tests.

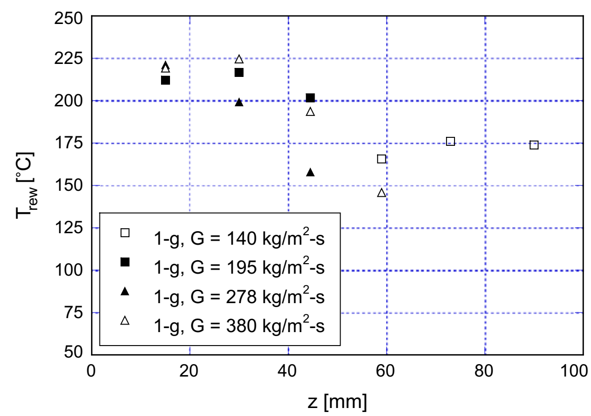

Fig. 10. Rewetting temperature versus axial location for 1-g tests.

necessary for the quench front to pass from one thermocouple position to the adjacent one (the distance of which is known).

Normal gravity tests, carried out under same thermal hydraulic conditions for comparison with microgravity data, have been performed on ground before and after the parabolic flight.

The results of the rewetting temperature, for reduced and normal gravity experiments, as a function of the mass flux are shown in Fig. 8, evidencing how the rewetting temperature does not look to be much affected by mass flux, spanning, on average, from 150 up to 250 °C. A slight reduction of the rewetting temperature is anyway evidenced as the mass flux increases. Within the experi-

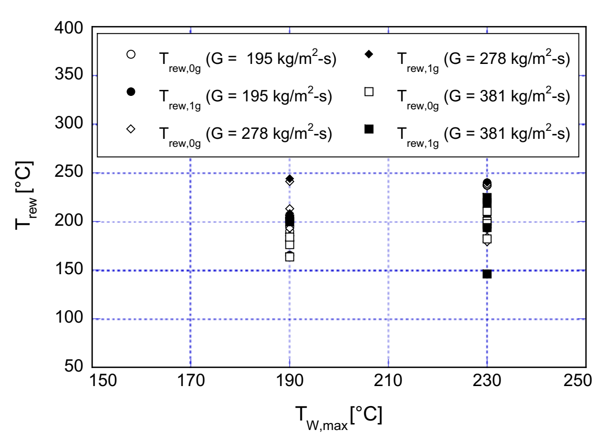

Fig. 11. Rewetting temperature versus initial maximum wall temperature for 1-g and 0-g tests.

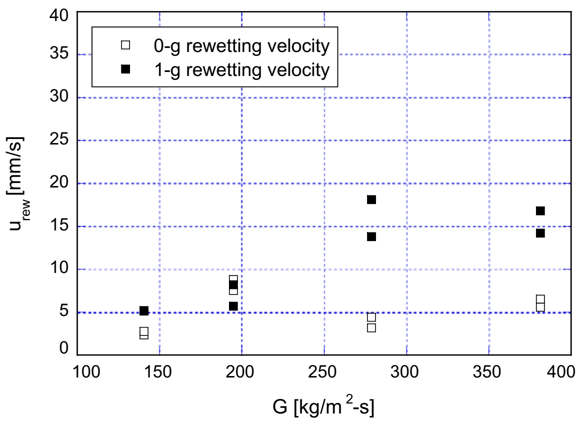

Fig. 12. Rewetting velocity versus mass flux for 1-g and 0-g tests.

mental uncertainty, the gravity level also looks to have little influence on the rewetting temperature, this latter only tending to be lower in microgravity, though the evidence is hardly visible.

Rewetting temperature is plotted versus the axial location in Fig. 9, for low gravity data, and Fig. 10, for normal gravity data, respectively, being data grouped according to mass flux. At low gravity, rewetting temperature is slightly affected by the axial position along the channel, while at normal gravity, the influence is more marked. On the other hand, the rewetting temperature close to the channel exit (bottom of the test section as the flow is upward) is a little bit lower than those measured at the inlet of the channel in both microgravity (slight difference) and terrestrial gravity (large evidence). All in all, as already found by Westbye et al. [2], the rewetting temperature in microgravity is typically 15–20 °C lower than at normal gravity.

Another interesting characteristic of the rewetting phenomenon is shown in Fig. 11, where the rewetting temperature is plotted as a function of the maximum wall temperature imposed at the beginning of the quenching experiment in microgravity and normal gravity, which is 160 °C, 190 °C, and 240 °C. For the wall temperature of 160 °C, there is no result in terms of rewetting temperature, as the wall temperature is below the rewetting temperature and the heated wall is wetted right away. As a consequence, the transient plot of the wall temperature does not exhibit the characteris-

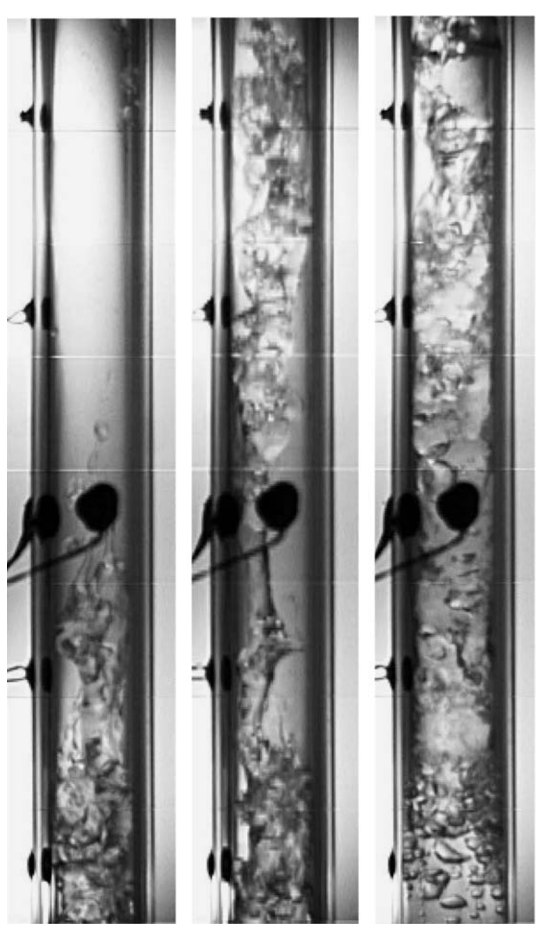

Fig. 13. Flow pattern at low mass flow-rate, $T_w = 235$ °C, terrestrial gravity.

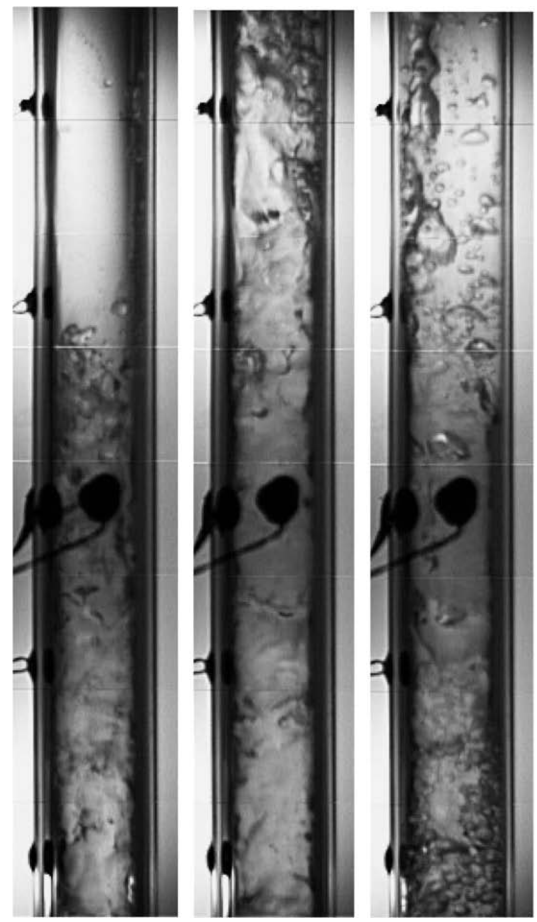

Fig. 14. Flow pattern at high mass flow-rate, $T_w = 235$ °C, terrestrial gravity.

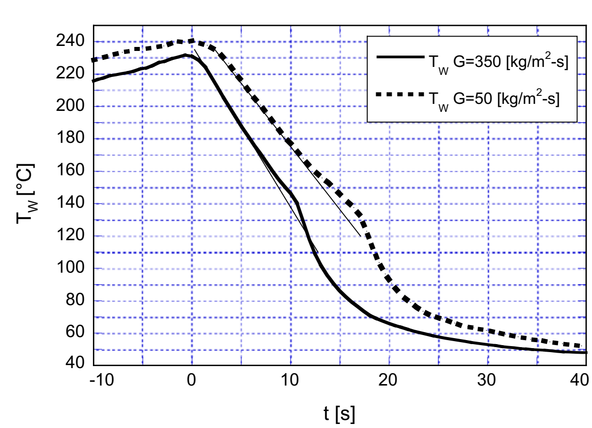

Fig. 15. Temperature traces during quenching of tubes with ITO transparent layer.

tic change of slopes which denotes transition from film boiling to nucleate boiling. For maximum wall temperatures of 190 °C and 240 °C, the rewetting temperatures are in the same ranges for all tests (different mass fluxes).

The results of the rewetting velocity as a function of mass flux for terrestrial and reduced gravity are shown in Fig. 12. The rewetting velocity indicates the speed at which the quench front moves from the inlet along the hot tube, which is also responsible of the whole tube rewetting time. Generally, the quench front velocity is significantly lower, often an order of magnitude lower, than the liquid velocity. In fact, the maximum liquid velocity (calculated as though the flow-rate occupied the whole cross-section) is 0.235 m/s, while the highest quench front velocity is 15 m/s. Fig. 12 clearly shows that the rewetting velocity at reduced gravity, is lower than that at normal gravity, other conditions being equal, the difference being more evident as the mass flux increases, reducing to about one third of the terrestrial gravity value. For low liquid mass flux the effect of the gravity level on the quench front velocity is less evident, though, with the exception of one data point, even at $G = 140$ kg/m^{2}s, the 0-g rewetting velocity is about 50% of that measured at terrestrial gravity. Increasing the mass flux, the quench front velocity at normal gravity is up to three times higher than that at low gravity. These results also show that, at normal gravity the rewetting front velocity is strongly dependent on the mass flow-rate, while at low gravity is definitely less sensible to the variation of the coolant mass flow-rate.

Although this is qualitatively in agreement with existing works [2–4] in the present work, we have information about the behaviour of the quench front speed due to changes in coolant mass flow-rates.

Four tests have been repeated to check the uncertainty in the process thus evidencing a significant scatter at terrestrial gravity, which this is very much reduced at low gravity.

4. Structure of the flow pattern

In order to unveil the flow pattern in the test tube and the influence of mass flow-rate during the quenching experiments, a new test section has been developed in the ENEA laboratories (which will be used for further campaigns planned in ESA parabolic flights). This test section is a pyrex tube with an ITO (Indium–Tin Oxide) coating deposited by sputtering technique on the outer surface. The metallic ITO layer has a thickness of less than 100 nm, and is transparent thus allowing fluid heating and simultaneous visualisation of the phenomenon inside the pipe. Figs. 13 and 14 show the flow structure at quenching for two different mass flow-rates at terrestrial gravity, where time is increasing from left to right, and the liquid is flowing upward.

The liquid front and the two main flow patterns, inverted annular flow and bubbly flow, are clearly visible in the pictures. Before quenching occurs we observe the inverted annular flow while at quenching the nucleate boiling takes place. The appearance of bubbles at the wall reveals the rewetting of the channel hot wall.

Frames in Fig. 13, recorded for $G = 50$ kg/m^{2}s (low mass flow-rate) with an initial wall temperature of 235 °C, show an inverted annular flow characterised by a high level of disorder. The liquid core is unstable, and is continuously disrupted during the test until

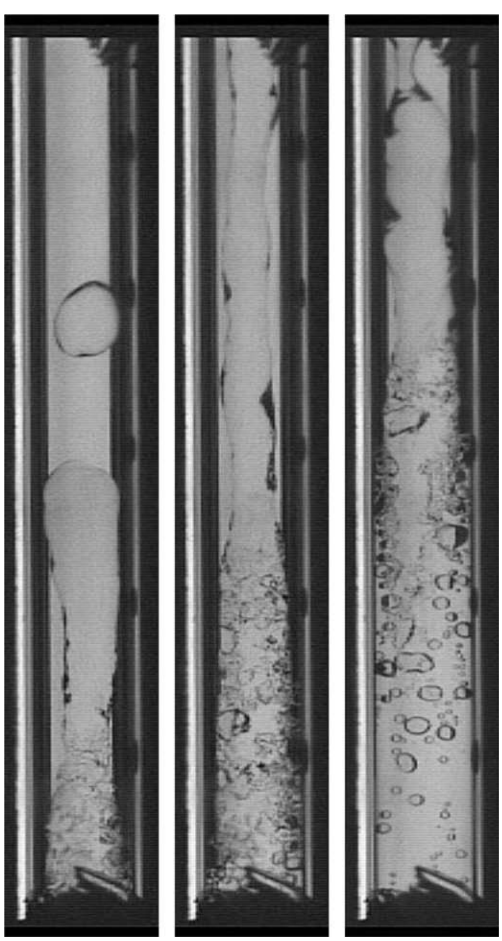

Fig. 16. Flow pattern at low mass flow-rate, $T_w = 235$ °C, low gravity.

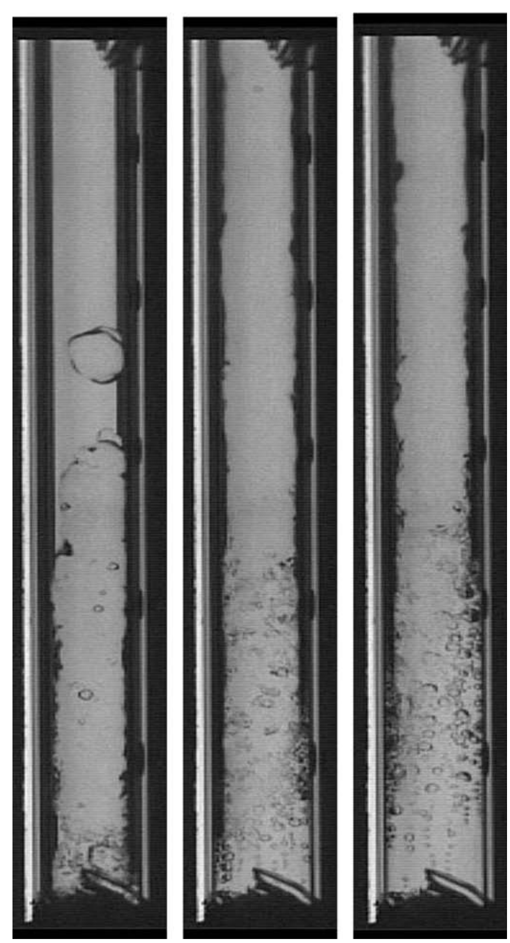

Fig. 17. Flow pattern at high mass flow-rate, $T_w = 235$ °C, low gravity.

the quench front appears. Also the liquid front shows a high level of deformation and disorder during its motion along the channel. The rightmost picture shows the appearance of the quench front at the bottom of the flow channel (presence of bubbles near the wall).

Flow pattern for higher mass flow-rate, $G = 350\ kg/m^2s$, is shown in Fig. 14. These pictures, taken at the initial wall temperature of 235 °C, show an inverted annular flow regime characterised by a very stable liquid core until the occurrence of quenching, again evidenced by the appearance of vapour bubbles at the bottom of the test tube (see the rightmost picture).

These 'ground' results would seem to confirm that mass flow-rate has a significant influence on the structure during the inverted annular flow regime. For low values of mass flow-rate the liquid core is irregular, continuously created and disrupted. For the higher mass flow-rate, the liquid core is more regular with a thinner vapour layer between the test tube and the liquid core.

Wall temperature traces for the two above described tests are plotted in Fig. 15. The beginning of quenching is indicated by the maximum value of the temperature when the liquid is injected in the hot tube ($t = 0$ s). After the liquid injection, the temperature slightly decreases in almost a linear way until a sudden change in the slope occurs. During this period (before and until the slope change) the flow pattern is inverted annular flow with film boiling. The sharp change in the temperature curve slope is defined in the previous paragraphs as the beginning of the rewetting process.

From the temperature curves it is possible to observe that just few seconds before the rewetting time the curves deviate from the linear behavior, revealing a reduction of the heat transfer coefficient, and showing that the quench front is strongly affected by the mass flow-rate. The temperature curve for high mass flow-rate, during the inverted annular flow regime (film boiling), is characterized by a higher slope than that of the temperature curve for lower mass flux. Therefore, the high mass flow-rate test is characterized by a shorter quench time thus evidencing a better cooling rate. If one consider also the characteristics of the flow pattern during the inverted annular flow, it is possible to conclude that the shape and the behavior of the liquid core both affect the cooling rate of the tube during quenching. When the liquid core is irregular and continuously formed and disrupted, then the quenching process is characterized by a longer quenching time. Viceversa, when the liquid core is regular and its shape is stable quench time is shorter. According to V.P. Carey [10], the stability of a vapour–liquid interface depends on the relative velocity between the two phases and is also linked to the gravity acceleration and to the fluid parameters such as surface tension and density of the two phases. Gravity and small values of the relative velocity of the two phases, stabilize the vapour–liquid interface. Therefore, when the liquid velocity is too small and the vapour–liquid relative velocity is high, the interface is quite unstable and the liquid core is irregular during the quench phenomenon. On the contrary, when the liquid flow-rate is high enough, and the relative velocity between the two phases is small, the interface is stable and the liquid core is characterized by a regular shape. Quench front velocity at low gravity is not influenced by mass flow-rates, maintaining its value in the range of 5–7 m/s. According to Carey [10], in the low gravity environment, the vapour–liquid interface is characterized by a high level of instability whatever is the value of the relative velocity of the two phases. Therefore, it is reasonable to expect that the liquid core behavior may be very similar to that observed at normal gravity for low mass flow-rates, with irregular shape chaotic behavior and, consequently, with lower cooling capability.

Pictures taken during a parabolic flight and shown in Figs. 16 (low mass flow-rate) and 17 (high mass flow-rate) would seem to confirm the idea that, other conditions being equal (i.e., the liquid subcooling), the mass flow-rate has a significant impact on the flow structure and on the quenching velocity.

5. Conclusions

An experimental investigation of quenching has been carried out with the objective to develop a data base under microgravity conditions to ascertain the gravity effect in quenching. The test tube is made of Pyrex with 6.0 mm in diameter. Tests are performed at normal gravity and in parabolic flight with vertical test section with liquid flowing upward, using FC-72. Measurements included wall temperature along the flow channel, inlet and outlet temperature, pressure and mass flow-rate. The results show that quench front velocity at low gravity is slightly affected by the mass flow-rate, maintaining its value in the range of 5–7 m/s, resulting much lower than the value obtained at terrestrial gravity under same conditions. Rewetting temperature is not affected by the gravity level and shows a slight reduction for the higher mass flow-rate. Keeping in mind that present tests are carried out at constant inlet liquid subcooling (25 °C) we can state that mass flow-rate has a significant influence on the structure and the behavior of the liquid core during the inverted annular flow regime. For low mass flow-rates, the liquid core is irregular and continuously formed and disrupted during the cooling process, while for higher mass flow-rates the liquid core is more stable and regular.

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