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Condensed-Matter Physics


Fig. 1


Fig. 2


Fig. 3

For many years now microgravity experiments in condensed-matter physics have been performed in available orbital vehicles in low Earth orbit. As a matter of facts, fluid phases are affected by gravity so that its suppression changes drastically the heat and mass transport in non-homogeneous systems. It also modifies the interaction of a fluid mother phase with a growing solid or crystal. Physical phenomena that are masked or changed on the ground by convection, sedimentation or hydrostatic pressure can be revealed or more easily observable in space. Microgravity research involves fluid phases with strong density gradients, like critical fluids, fluid-fluid interfaces (foams, emulsion…) and fluid-solid interfaces (solidification and crystal growth).

Microgravity can be achieved by counter-balancing the weight by another volume forces (non-inertial ones like in magnetic gradient levitators that are operated on the ground, or inertial ones in the case of satellites or drop towers). Microgravity installations are thus large instruments for research, as observatories or synchrotrons. Microgravity research is thus a branch of space sciences. It is also a non-reducible component of the space environment to which space technologies must adapt for deep space exploration and that can take advantage of the acquired fundamental knowledge.

Context of microgravity research in France

Forty laboratories or so are involved in the program, among which thirty one are funded by the French Space Agency. These laboratories are put together in a common managing structure with the Centre National de la Recherche Scientifique (CNRS) and the French Atomic Energy Commission (CEA), called Groupement de Recherche Micropesanteur Fondamentale et Appliquée (GdR MFA).

French microgravity utilization program is divided into two parts, the bilateral program where France conducts bilateral cooperation with other agencies, and the European Program where France has access to the European facilities of the Colombus module (Fig. 5) in the International Space Station (ISS).

The main piece of the bilateral program is the DECLIC (DEvice for the study of Critical LIquids an Crystallization) developed by CNES and commonly exploited with NASA (Fig. 1 and 2).

ESA program

The following experiments have been performed up to now: GEOFLOW, which is the simulation of geophysical flows; FASES to study emulsions; SODI to measure the Soret coefficients in ternary mixtures; CETSOL to study the transition between columnar and equiaxed transition during the solidification of metallic alloys (16 samples have been processed among 40); MICAST, dedicated to the study of solidification under magnetic field (10 samples have been processed among 40). Since the beginning of the exploitation of Columbus, total operational time dedicated to the European Program for Life and Physical Sciences in Space *(ELIPS)* has amounted to 2 500 hours or so, for all of Europe.

DECLIC facility

The facility has been developed within the framework of a NASA-CNES cooperation, in which CNES funded and built the facility and its inserts while NASA covered the launch and operational costs.

The facility is made of a service module with diagnosis and stimuli that can host alternately various inserts dedicated to different science objectives: physical properties of supercritical water with the High Temperature Insert, HTI; phase transitions in room temperature supercritical fluids (boiling crisis, measurements of Ising coefficients very close to the critical point) with the Alice Like Insert (ALI); dynamics of microstructures during the solidification of bulk model alloys with the Directional Solidification Insert (DSI). The facility is operated from the ground from the CADMOS center in the Toulouse space center of CNES. The possibility to upgrade the inserts after bringing them back to the ground made it possible to extend the initial research program and to pursue the cooperative research program. The HTI Insert has been retrieved

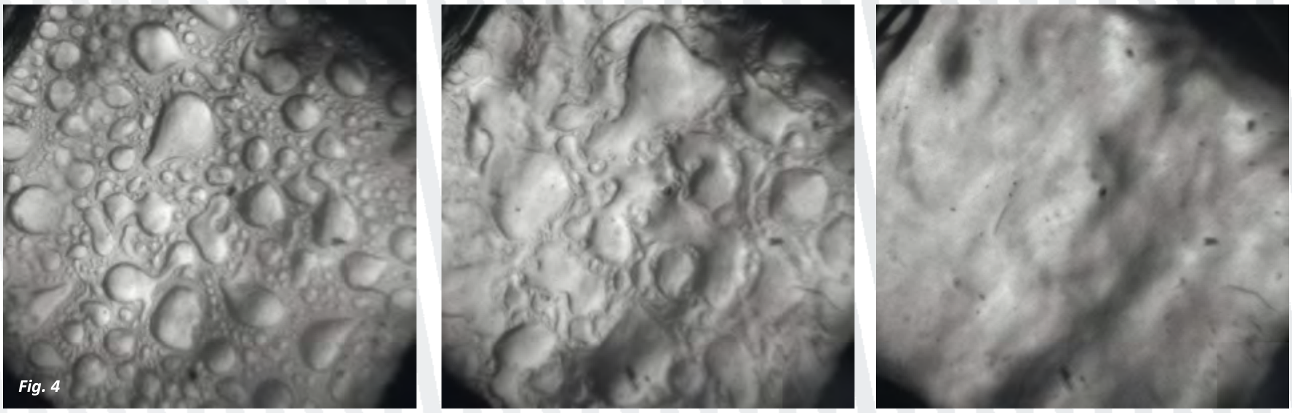
Fig. 4

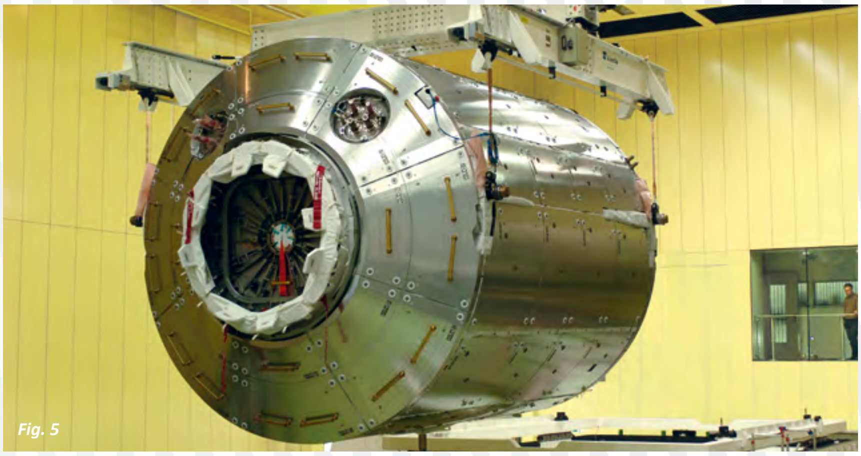
Fig. 5

on the ground and loaded with salt water to study the dissolution of salt in the vicinity of the solubility critical point within the framework of a NASA-led cooperative program. The DSI insert has been brought back to Earth to change the alloy concentration.

Installed in the Japanese module under NASA-JAXA barter, DECLIC has worked for 12 000 hours or so without any major failures since its launch in 2009. It has worked about 6 000 hours during the past two years and one can say that it is a scientific, technical and operational success.

Sub orbital and ground-based experiments

The parabolic flight using the Airbus A300 ZERO-G is a baseline element of the activity. It allows for short term, regular and well planned experiments and technological tests. The quality of the results, especially in the field of bio fluid physics for example, and the number of research groups that make use of this facility led CNES to make the decision to replace the ageing Airbus A300 by a newest Airbus A320 in 2015. One should mention that the combustion research is again very active in the field of flame propagation, in monodisperse fuel droplet suspensions and in the field of solid fuel flammability. Cooperation with JAXA is currently being discussed. The magnetic levitation facility developed in the Grenoble center of the Atomic Energy Commission has been upgraded. It is now able to levitate 50 cm^3 of liquid hydrogen and to mimic transient acceleration corresponding to the engines shutdown and re-ignition with a particular attention on the geyser formation dynamics and the heat exchanges coefficients under various gravity levels (Fig. 4).

Future prospect

A prospective seminar was held in 2014 to define the scientific priorities of the French community. The main recommendation of this community was the development of a new facility to replace DECLIC after 2018. This DECLIC-NG facility would be conceived under the same architecture: a main body with diagnosis and electronic units that hosts inserts dedicated to specific research themes. NASA and CNES envision pursuing the collaboration: CNES would fund the development and NASA would cover the launch and operational costs. A three years development is foreseen which would lead to a launch date by the end of 2018.

[Fig. 1]
DECLIC instrument at the CADMOS center in Toulouse. © CNES/BARRANCO Rachel, 2013

[Fig. 2]
Launch of the DECLIC facility to the ISS, on August 29, 2009. © ESA/NASA, 2009

[Fig. 3]
The International Space Station (ISS) photographed by a member of the STS-130 mission. © NASA, 2010

[Fig. 4]
Visualization of the critical heat flux as observed in the magnetic levitation device in CEA Grenoble. From left to right: nucleate boiling, transition and film boiling. © CEA

[Fig. 5]
Columbus laboratory. © ESA, 2008

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Condensed-Matter Physics

Hydrodynamic instabilities observed in evaporating droplets

Instabilités hydrodynamiques observées dans des gouttes en évaporation

➔ **Abstract:** When a droplet of ethanol is under evaporation, invisible to the naked eye, hydrodynamic instabilities develop therein and can be observed in the infrared. These instabilities that affect the local temperature fields (*i.e.* evaporation) are the source of many problems in drying of complex fluids (paints, inks, cosmetics). On Earth, the phenomenon is also influenced by the gravity changes in complex fluids deposit after evaporation.

➔ **Résumé :** Lorsqu'une goutte d'éthanol s'évapore, des instabilités hydrodynamiques invisibles à l'œil nu se développent en son sein et sont observées dans l'infrarouge. Ces instabilités qui affectent le champ de température local (donc l'évaporation) sont à l'origine de nombreux problèmes rencontrés lors du séchage de fluides complexes (peintures, encres, produits cosmétiques). Sur Terre, le phénomène est aussi influencé par la gravité qui modifie pour les fluides complexes le dépôt après évaporation.

The topic of sessile droplets evaporation has rapidly increased in terms of publications for the last ten years especially due to its applications; for example for droplets of DNA or colloids in inkjet printing. Nowadays, droplets of pure fluids are studied since they can exhibit flow instabilities or complex triple line motions on new substrates with complex topologies. Droplets of complex fluids including biological fluids and nanofluids are the topic of many research activities and almost nothing exists in the literature. For both these situations, droplet evaporation physics is complex including fluid mechanics, heat transfer, wettability and surface chemistry. These activities are funded by CNES in the frame of multiple space projects: Arles is a European experiment onboard MASER 13, Impacht a French-Chinese experiment onboard a Chinese scientific satellite SJ-10 and Drop Evaporation in the Thermal Platform onboard the ISS.

The influence of terrestrial gravity in a sessile drop under evaporation is not at all negligible, as can be seen in Table 1 of Carle *et al.* [1]. The dynamic Bond number is the ratio between the Rayleigh and Marangoni numbers. This dimensionless number reflects the competition between the thermo-gravitational and thermo-capillary phenomena. Thermo-capillary phenomena on Earth are dominant but induce changes on evaporation on both dynamics of evaporation (see Fig. 1 and the online movie on the site of JFM [1]) but also on the temperature gradient at the interface of the droplet (Fig. 2).

The use of a microgravity environment induces a 113-fold decrease of the static Bond number and a 74-fold decrease of the dynamic Bond number. Under normal gravity, thermo-convective effects are dominated by thermo-capillary ones but are not negligible (Bd = Ra/Ma = 0.08) whereas under microgravity, only the thermo-capillary effects exist (Bd = 0.00106). Under normal gravity, a temperature gradient develops during the evaporation from the apex of the droplet and the contact line, resulting in a gradient of surface tension. This gradient then generates thermo-capillary instabilities. These hydrothermal waves (HTWs) propagate radially around the apex, where most of the evaporation occurs. The HTWs are spaced by an almost constant angle along the axial symmetry of the triple line. Two different spatial dynamics were observed. The HTWs were found to run ortho-radially around the edge of the droplet either from a source point where they are established to a well where they collapse or all in the same direction but with no preferred direction (clockwise or anticlockwise), depending on the temperature of the substrate and the height of the droplet. Under microgravity, the temperature gradient is not as well defined as it is under normal gravity, but the apex maintains a temperature below the temperature of the triple line. In this configuration, HTWs have the same trend, but their movements are not as systematic as they are under normal gravity. Instabilities develop during the transitional phase. During the quasi-stationary regime, the HTWs propagate from a source point to a well. These instabilities also propagate on the edge of the droplet, but the angle of propagation is not as constant as it is under normal gravity. This change in propagation could be caused by the vibrations of the aircraft, which cause significant fluctuations in the level of microgravity. Despite this lack of stability, the evolution of the number of HTWs is similar under both gravitational conditions.

Despite this dominance of thermo-capillary effects, the low contribution of gravity on Earth therefore alters the evaporation and mainly influences the internal fluid mechanics. On Earth, when the substrate is heated, the contribution from the thermo-gravity convection in the vapor phase becomes dominant. In weightlessness, our first experiments in parabolic flights reinforce the purely diffusive model. We also

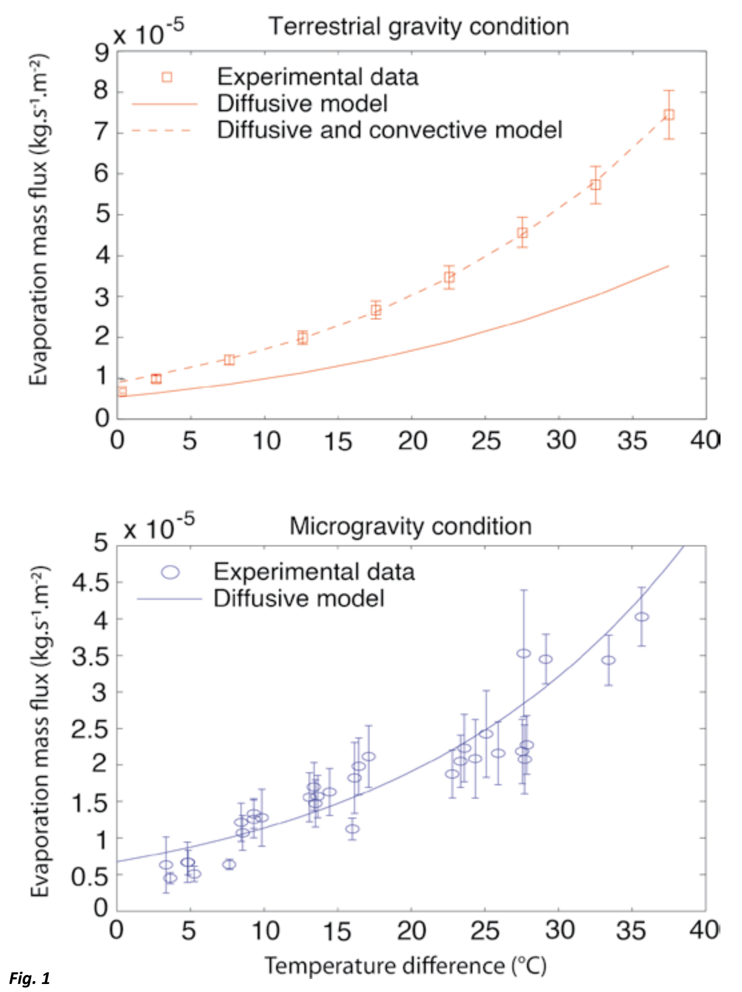

Fig. 1

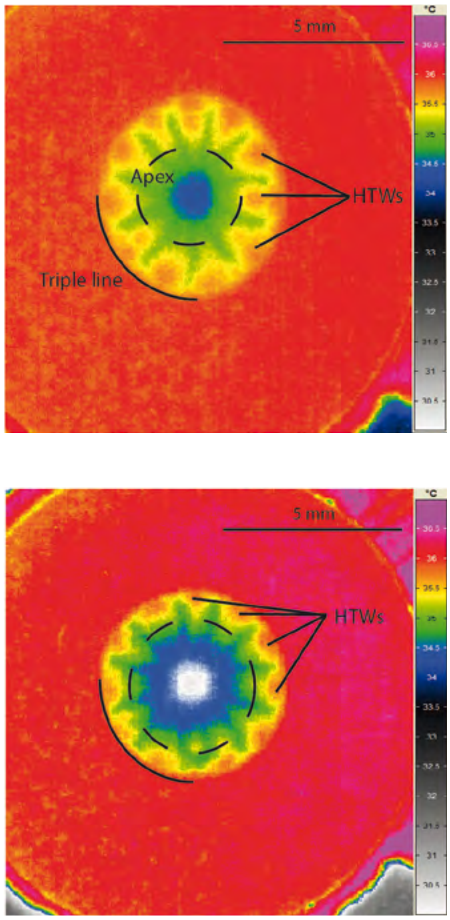

Fig. 2

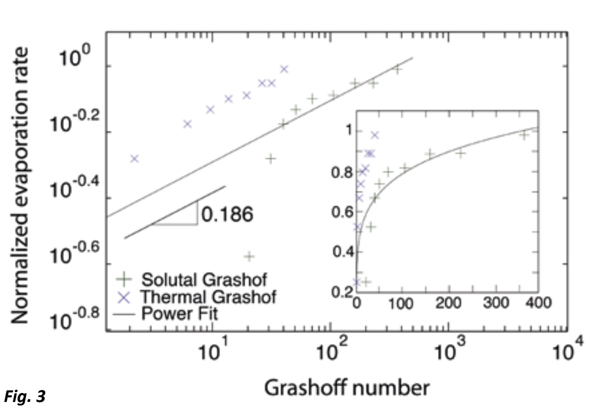

Fig. 3

[Fig. 1]
Evaporation rate by unit length of an ethanol sessile droplet as a function of the temperature difference between the substrate and the ambient air for 1 g (top) and microgravity conditions (bottom). © David Brutin

[Fig. 2]
Infrared visualization of ethanol droplets under normal gravity (up) and reduced gravity (down). © From [1]

[Fig. 3]
The variation of the dimensionless convective evaporation as a function of the Grashof number on a log-log scale. The inset shows the same data in Cartesian coordinates. © David Brutin

have, through these experiences in parabolic flight, finally demonstrated that hydrothermal waves observed in evaporating drops are purely of thermo-capillary nature [2] that had never been proven (Fig. 3). Our current studies show that the diffuso-convective model (including the influence of gravity) only works for classical fluids (water, ethanol). However this model is not quantitative when other alcohols or alkanes are used [3]. Our current work, supported by CNES, is to understand the origin of these differences in order to provide a universal model.

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Condensed-Matter Physics

Hydrogen boiling study in magnetic levitation for cryogenic propellant simulation

Etude de l'ébullition d'hydrogène en lévitation magnétique pour la simulation des ergols cryogéniques

➔ **Abstract:** For developments of future cryogenic upper stages of space launchers, a modeling, through CFD tools, of propellant behavior, especially during ballistic phase, is necessary. The boiling of hydrogen is a main phenomenon to take into account. An experimental magnetic levitation was used to obtain precise data on hydrogen boiling under microgravity condition.

➔ **Résumé :** Pour le développement des futurs étages supérieurs cryogéniques de lanceurs une modélisation par des outils de CFD du comportement des ergols, en particulier lors des phases balistiques, est nécessaire. L'ébullition de l'hydrogène est un phénomène important à prendre en compte. Un dispositif de lévitation magnétique a été utilisé pour obtenir des données précises sur l'ébullition de l'hydrogène dans des conditions de microgravité.

Prediction of the behaviors of cryogenic liquid propellant in microgravity is a key element for decreasing development risk and optimizing design of a new generation of cryogenic upper stage. Computational Fluid Dynamics (CFD) tools will be used to model the cryogenics propellant behaviors during all the phases of a space launch: from the tank pressurization on the launch pad up to the end of the draining of the upper stage tank. This will include the ballistic phases when propellants will be in microgravity condition.

Important work has been performed in the past decade. CNES and Air Liquide Advanced Technologies have developed through a partnership innovative models to be used with a commercial CFD tool. Those models mainly focused on thermal aspect, were validated through analysis of laboratory's experiments, but also with microgravity experiments using magnetic levitation devices or parabolic flights.

However, two main types of data are missing:

- Data concerning heat and mass transfer on walls for cryogenic propellant (liquid oxygen and liquid hydrogen) in low gravity.
- Global behavior of cryogenic liquid in tanks (temperature and pressure evolution coupled to free surface behavior).

For this first point, experiments using magnetic levitation apparatus have been developed. Indeed, partial or total compensation of Earth gravity *(g)* can be achieved for solid, gas and liquid phases of pure materials when submitted to a steady magnetic field gradient. This has been the object of the OLGA (Oxygen Low Gravity Apparatus) facility which works with pure oxygen and of the LHYLA (Large Hydrogen Levitation Apparatus) facility which works with pure hydrogen.

The use of magnetic levitation has some advantages for our application:

- To be able to wait for established phenomenon (no constraints to get thermally stabilized points).
- To use different gravity values in order to have the real influence of this parameter.
- To know precisely the residual gravity field.

Due to the low magnetic susceptibility of hydrogen, a high magnetic field is necessary to compensate gravity. So a 20 Tesla high field magnet with its 170 mm room temperature bore diameter was used called M8 (Fig 1.) at CNRS/LNCMI (Laboratoire National des Champs Magnétiques Intenses). This magnet is composed of two resistive subcoils that can be powered independently. Consequently the balance between the power injected in the inner coil to the one of the outer coil allows a fine tuning of the levitation condition. For the hydrogen experiments, 14 T magnetic field was used, giving a levitation volume of several cm^3 with 1% microgravity homogeneity. The large bore diameter of this magnet permits to place the experimental cell within cryogenic sample environment

The two experiments OLGA and LHYLA work with the same cylindrical cell (Fig. 2) developed by CEA/SBT (Commissariat à l'Energie Atomique / Service des Basses Températures – French Atomic Agency / Cryogenic Department). The sapphire cylinder (30 mm diameter and 100 mm length) is closed by two copper flanges, the temperature of which is regulated within ± 0.01 K. The oxygen or hydrogen, taken from a gas bottle is condensed into the cell respectively at 90 K or 20 K. The cell is isothermal. Oxygen and hydrogen are kept at constant temperature during the experiments. A heater is implemented on the bottom of the test cell.


Fig. 1

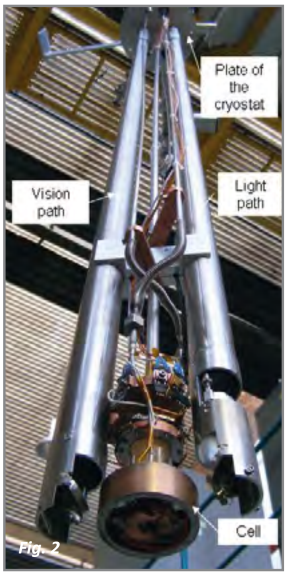

Fig. 2


Fig. 3

Fig. 4

Thanks to LHYLA apparatus, boiling data were obtained for liquid hydrogen for different gravity values and other parameters variations representative of tank conditions (pressure, sub-cooling level) (Fig. 3). These data and associated boiling behavior were also compared to numerical code.

This work was performed by CEA/SBT and CNRS/LNCMI and was supported by CNES.

[Fig. 1]
M8 magnet at CNRS/LNCMI. © CNRS/LNCMI

[Fig. 2]
Photography of the experimental cell with its endoscopes developed by CEA/SBT.
© CEA/SBT

[Fig. 3]
Hydrogen bubbles created by boiling close to 0 g condition.
© CEA/SBT

[Fig. 4]
Picture of the launchers Ariane 5 ME and its successor, Ariane 6.
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Condensed-Matter Physics

Non-equilibrium triple contact line motion observed in DECLIC on board the ISS

Mouvement de la ligne triple gaz-liquide-solide hors-équilibre observé avec DECLIC dans l'ISS

➔ **Abstract:** Non-equilibrium motion of the triple contact line was observed when a two-phase fluid sample is heated close to the critical temperature of the fluid. Instantaneous drying of the liquid wetting film occurs between the bubble and the heating wall, while liquid boiling enhances the bubble spreading over the heater surface. Motion velocity of the triple contact line was precisely measured and will later be compared to theoretical approaches and numerical simulations under development.

➔ **Résumé :** Le mouvement de la ligne triple gaz-liquide-solide hors-équilibre a été observé lors du chauffage d'un fluide pur diphasique proche de la température du point critique. Le film de liquide entre la bulle et la paroi chauffante s'assèche instantanément et l'ébullition dans le liquide favorise l'étalement de la bulle. La vitesse de déplacement de la ligne triple de contact a été mesurée avec précision et pourra être confrontée aux théories et aux simulations numériques en cours de développement.

One of the most effective means of heat transfer is the boiling phenomena of a liquid in contact with a solid heater. Such a heating process attracts strong attention from thermal engineers, especially when boiling crisis occurs, which may produce an irremediable damage to a heat exchanger via the heater melting. Indeed, boiling crisis is a transition from a regime where vapor bubbles nucleate separately on the heater wall to a regime where the heater wall is entirely covered by a continuous vapor film (dry out process). When formed, the vapor film reduces the heat transfer dramatically at the heater wall, due to the low gas thermal conduction. This transition phenomenon appears when the heat flux exceeds a threshold value, called the Critical Heat Flux (CHF) [1]. Understanding the physics of the CHF is thus essential in industrial heat exchanger design and thermal management. However the desired identification of the phenomena that trigger the boiling crisis process is complex.

Experiments remain an essential way to discriminate the mechanisms governing the bubble formation and growth, the bubble detachment and/or spreading, as well as the vapor film formation and stabilization. Furthermore, the experimental conditions in which the critical dry out occurs make a true challenge for any detailed analysis, especially on Earth when deeper understanding of the boiling crisis under the gravity acceleration field is essential. The main reason is the highly non-equilibrium nature of the boiling crisis, which makes a study in steady state conditions impossible. It can only be studied during the very short transient period when the crisis takes place, which enhances the experimental difficulty of collecting pertinent data.

Investigations to evaluate boiling crisis mechanisms have been carried out free of buoyancy effects in a two-phase fluid in weightlessness, where the formation of spherical bubbles occurs. Here, microgravity experiments were performed in the DECLIC facility [2] onboard the ISS, using test cells [3] filled with SF6 near the critical density, just below its critical point temperature (T_c = 318.737 K). These experiments close to gas-liquid critical point overcome the high instability of the process by taking benefits from the universal slowing down giving a longer time for all the diffusive equilibration processes. This entails the evaporation process and the bubble growth slowing down as approaching the critical point. In addition, the convergence of the liquid and gas densities, associated to the reduction to zero of the surface tension, implies a steep decrease of the CHF value [4], so that the boiling crisis can occur for small heat powers and small temperature gradients.

The initial microgravity configuration of the gas-liquid phase distribution at thermodynamic equilibrium corresponds to a large gas bubble slightly confined in the inner volume of the test cell. Thus, a thin liquid wetting film separates the gas bubble from a flat, transparent resistive heater, which can be tuned as a local heating source of controlled power and duration. During the heat pulse, simultaneous light transmission observations show the liquid film drying and the displacement of the triple contact line between bulk liquid, gas, and solid. As an example using the optical microscopy (1x1 mm^2 field of view) during a heat pulse 1 mW power, 33 s duration, supplied at 1.5 mK temperature distance below T_c, the two movie pictures of Fig. 1a and 1b capture the two different positions (highlighted by a red line) of this non-equilibrium line between the two pulse times +1 s (a) and +29 s (b). Close to the critical point, the complete drying of the liquid film is observed quasi-instantaneously in the gas right side of the moving (from right side to left side in the pictures) triple contact line. Simultaneously, the boiling phenomena at the origin of the dry out process of the bulk liquid in contact with

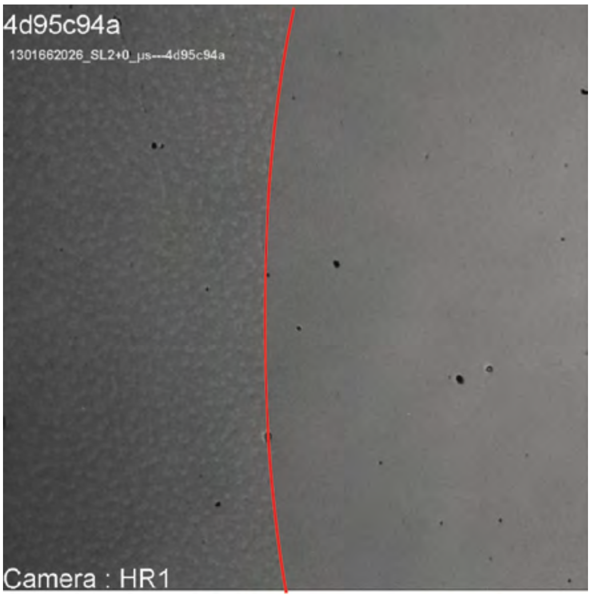

Fig. 1a

Fig. 1b

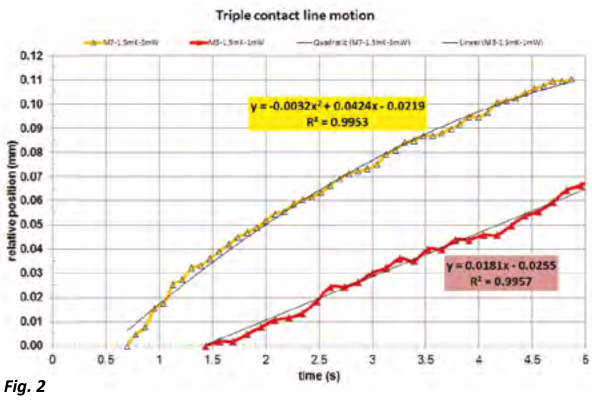

Fig. 2

[Fig. 1]
Microscopy observations, at $T = T_c - 1.5$ mK, of the triple contact (red) line motion from t_0+1 s (a) to t_0+29 s (b), during a thermal pulse (1 mW power, 33 s duration) supplied at t_0. Complete spreading of the gas bubble is noticeable on the right side of the red line, while boiling occurs on the liquid left side.
© ICMCB/CNRS

[Fig. 2]
Time-position measurements of the non-equilibrium triple contact line for two heat pulses of different powers 1 (red) and 3 (yellow) mW, 33 s duration each, at $T = T_c - 1.5$ mK, using ALI-DECLIC onboard the ISS. Continuous lines: polynomial fitting of the instantaneous position, providing access to the triple contact line velocity.
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the transparent heater is also observed in the liquid left part of the moving triple contact line. The time dependence of the triple contact line position (Fig. 2) gives access to its local velocity from a polynomial fit of the recorded data for different heating conditions, which can be estimated of the order of a few tens of µm.s^{-1}, using the two examples illustrated by the corresponding fitting blue lines.

Complementary details and additional references can be found in [5] where collected experimental data have also provided new observations of the gas bubble spreading over the heating surface, the vapor bubble nucleation and growth, and the vapor film formation. All these key mechanisms will provide a new route toward a better understanding of the boiling crisis, especially focusing data analyses on the recently suggested zero-value of the CHF, which places the boiling crisis in weightlessness in the context of the critical dynamics of non-equilibrium systems.

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