[PHYSICS IN SPACE]

BUBBLES, DROPS, FILMS: TRANSFERRING HEAT IN SPACE

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Phase-change phenomena play an important role in our daily life. They are of great interest for cooling electronic components or engines. They are also used in vapour generators. At least two thirds of the electrical energy produced in the world uses this technique. Two-phase flows are also present in space applications: energy production, electronic cooling devices and, as one can expect in the future, in waste water treatment and life support systems for long-duration space exploration missions. So, in many applications high heat fluxes are achieved by utilising the latent heat associated with the phase change from liquid to vapour. However, the physical mechanisms involved are intricate and many questions remain unanswered: how does a bubble nucleate on a heated surface? When will bubbles completely cover a hot surface? What is the amount of heat transferred by boiling evaporation or reversely, by condensation?

The field clearly is at the crossroads of thermodynamics, fluid dynamics, materials sciences and physical chemistry of interfaces. Because of the complexity of the coupling effects in systems involving phase change and the lack of reliable prediction capabilities, the development of industrial devices is essentially based on empirical rules. Their utilisation then relies on correlations established between operational parameters and heat transfer performances, which cover a limited range of parameters and thus cannot be extrapolated to other situations and in particular to a microgravity environment.

Progress in the field requires a better understanding of the basic mechanisms and the development of predictive capabilities. This is supported by recent advances in measurement techniques and an increase in computing performances. It is however still difficult, if not impossible to discriminate between these individual basic phenomena.

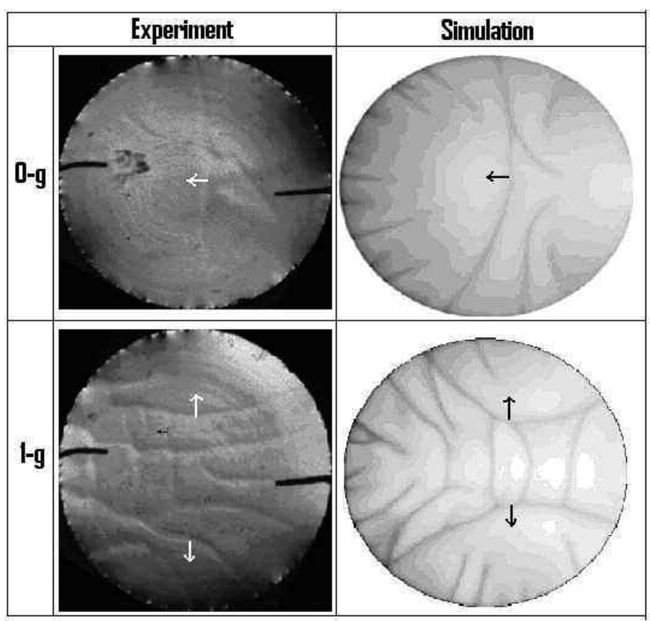
Phase change occurs at interfaces, the boundaries separating different phases. Although molecularly thin, liquid-gas interfaces play a major role in the overall behaviour of the system. It is therefore crucial to understand the details of their static and dynamic behaviour. Because of the principle of minimal surface energy, an interface ideally tends to assume a spherical shape. However, on Earth, the gradient of hydrostatic pressure leads to the flattening of drops and elongation of bubbles. In a flow, viscous and inertia effects are also responsible for pressure gradients and thereby, for interface deformation. In liquid-vapour flows, the density difference is very high and gravity effects dominate capillary and viscous effects. Gravity generates thermal convection and causes bubble detachment during boiling and stabilises liquid films. Under normal gravity it is thus impossible to separate the various mechanisms involved.

Microgravity is a good tool to improve the quantitative understanding of these physical mechanisms. Experiments have been performed in free-fall conditions at different time scales demonstrating the relevance of two-phase flow studies in space. Several instruments have been defined in the frame of international programmes and planned for the International Space Station in order to extend these investigations.

Three different configurations employed for heat transfer are discussed here: evaporation and condensation of liquid films, pool and convective boiling, and spray cooling.

Liquid films with evaporation and condensation

When a liquid evaporates non-uniformly in the air, temperature gradients form along the interface, resulting in a varying value of the surface tension along the interface. This induces thermocapillary flow, known as the Marangoni effect. Even when evaporating uniformly, a liquid layer does not remain quiescent but is subject to hydrodynamic instabilities [1] generating intense motions. On Earth, these motions cannot be clearly dissociated from buoyancy convection due to density variations associated with thermal expansion. Experiments on sounding rockets however [2], have already confirmed the predicted occurrence of convection patterns in evaporating liquid layers (see Figure 1). More detailed investigations of these patterns over a wider range of parameters are already planned to be performed on the ISS.



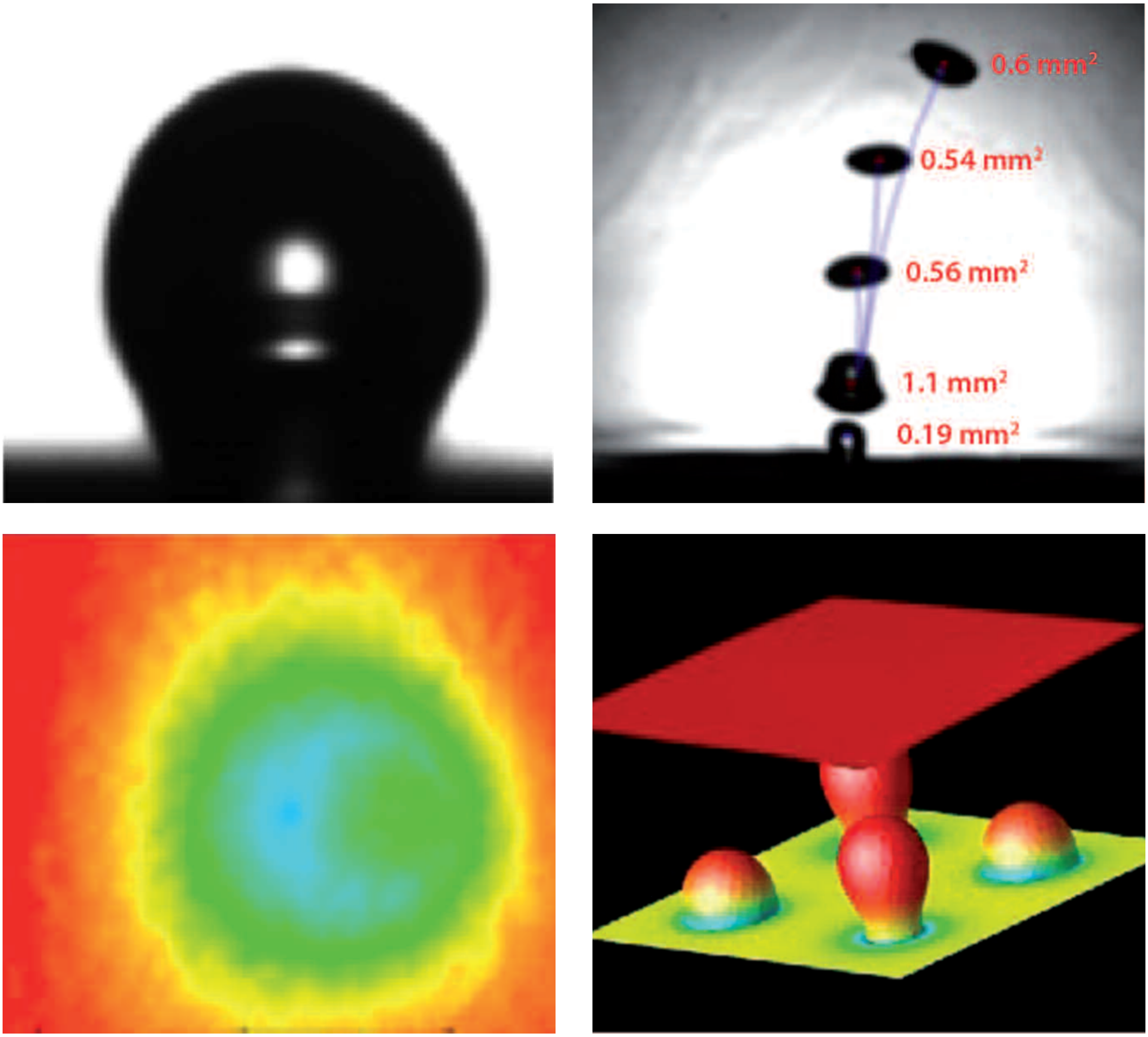
▲ **FIG. 1: Convective patterns in an evaporating 5 mm layer of ethyl alcohol above which a flow of dry nitrogen gas is established from left to right at a rate of about 330 ml/min. The pressure is about 650 mbar. The snapshots show ripples moving at the interface either upstream in microgravity (0g) or laterally in ground conditions (1g), as indicated by the arrows.**

Furthermore, thermocapillary effects may also induce the rupture of thin liquid films evaporating on a hot substrate or flowing along it, *e.g.* in the gravity field [3]. As the temperature of the fluid increases, its surface tension decreases and the resulting surface tension gradient produces a flow opposed to the gravitationally driven flow. This results in a liquid bump in the region of the upper edge of the heating element. Beyond a critical heat flux, rivulets (small 'rivers') start to form at the bump position. They are aligned with the flow and distribute spanwise with a fixed wavelength. If in addition a gas is blown along the liquid-gas interface, waves form parallel to the stream, but with a much smaller wavelength. Under free-fall conditions, surface tension effects dominate such that a liquid film in a horizontal channel becomes a flattened rivulet.

Similarly, the vapour condensation on a cold surface results in either a wetting film or droplets; both gravity and surface tension effects contribute to controlling the flow even if structured surfaces are used as in industrial devices. Condensation is therefore also a subject for future space experiments [4].

Pool and convective boiling

Nucleate boiling occurs when a liquid is in contact with a surface maintained at a temperature above the saturation temperature. Vapour bubbles then nucleate, grow and detach from the heated wall under the effect of gravity and/or liquid flow entrainment (convective boiling). The design of new processes and evaporators is significantly hindered by the fact that general computational techniques and analytical methods are not yet



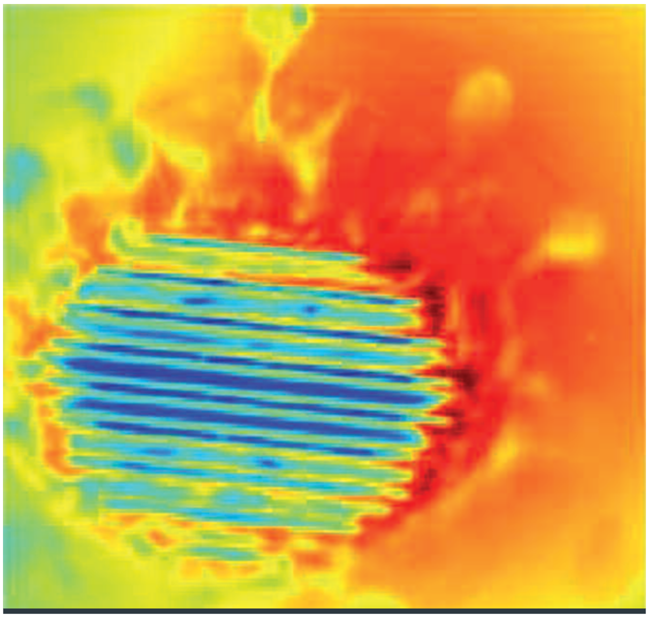
▲ **FIG. 2:** Simultaneous sideway observation of a single vapour bubble at an artificial nucleation site in microgravity **(top left)** and vertical observation from below of the heating wall that is covered with a layer of temperature sensitive liquid crystals **(bottom left)**. Bubble detachment in normal gravity **(top right)**. Direct Numerical simulations of bubble growth on a heated plate **(bottom right)** also in normal gravity (**www-trio-u.cea.fr** - in french) available. The existing correlations between the parameters (*e.g.* fluid properties, heater geometry, gravity) and the system performances lack physical contents.

Several European research teams have joined efforts to improve the quantitative knowledge of nucleate boiling. The most sophisticated models for the prediction of the wall heat transfer can include details at the level of single bubbles. Therefore, models of the thermodynamic and hydrodynamic phenomena at different scales have to be developed and experimentally verified by a wide scanning of the parameter space. Vapour bubbles grow from microscopic surface cavities, so called nucleation sites, at the heated wall. The very tiny zone where the vapour inside the bubble and the surrounding liquid meet the heated wall is of significant importance for the heat transfer. Near this three-phase contact area, which is about one-micron wide, the evaporation rate is extremely high and induces a strong local cooling of the heated wall (Figure 2, bottom left panel). This observation was confirmed during micrograms experiments: indeed, in the absence of buoyancy, the growth rate of the vapour bubbles is slowed down and their detachment is delayed, which enables measurements at higher spatial and temporal resolutions [6]. Such high local evaporation rates can now be predicted by advanced models of transient nucleate boiling. These models can in turn be used as sub-grid models at the contact line in advanced numerical methods for the computation of the growth of several bubbles on a heated wall (Figure 2). Additionally, the hydrodynamic effects of a liquid shear flow [5,7,8] and the effect of an electric field upon the bubble to compensate for the absence of buoyancy [9] are also investigated in normal and microgravity conditions.

Spray cooling

A spray impacting onto a rigid wall creates an oscillating liquid film on its surface which is then completely or partially covered. The flows produced by the spray impact can take a variety of patterns such as jets, sheets, crowns and capillary waves [10]. In many cases the free liquid sheets are unstable and break up into secondary drops. The inertia of the impacting droplets is the main cause for the near-wall two-phase flow. In addition, the flow morphology is determined by gravity, by the surface tension and the wetting behaviour of the liquid, by the geometry of the wall and by the phase change. The most prominent effect of phase change can be observed when the wall surface temperature exceeds a critical temperature called Leidenfrost temperature. In this case the impacting liquid droplets remain separated from the surface by a thin vapour film. They evaporate partially or completely without direct contact with the hot wall.

Below the Leidenfrost temperature, each impacting droplet of cold liquid contributes to the cooling of the hot wall surface. The heated liquid then flows away because of the combined effects of inertia and gravity. In reduced gravity the removal of the hot liquid from the surface is slower than in terrestrial conditions. This results in an increase of the liquid film thickness and a reduction of the cooling performance [11]. Consequently, it also reduces the film evaporation rate, which is an important cooling mechanism if the wall temperature is close to or exceeds the saturation temperature.



▲ FIG. 3: **Infrared image of a single drop impacting onto a heated liquid film on a grooved wall. The grooved wall surfaces are used for heat transfer improvement. The drop impact created a crater in the liquid film (a large round area with irregular boundaries), which resulted in liquid dry out at the groove crests. The groove troughs are filled with cold liquid of a drop. Secondary droplets produced by the splash are seen around the crater area.**

Gravity also has a considerable effect on the near-wall flow [10]. In particular, gravity influences the size of the crater produced by a single drop impact on a liquid film. Gravity affects the film thickness inside the crater and thus, the conditions of the splash (Figure 3). These effects have to be firstly completely understood, measured in microgravity and modelled in order to describe, analyse and ultimately optimise spray cooling on Earth and in space. ■

References

[1] B. Haut and P. Colinet, *J. Colloid Interface Sci.* **285**, 296, 2005.

[2] P. Colinet *et al.*, *Adv. Space Res.* **32**, 119, 2003.

[3] A.M. Frank, O.A.Kabov, *Phys. of Fluids* **18**, 032107, 2006.

[4] O.A. Kabov *et al.*, *Microgravity Sci. technol.* **XIX (3/4)**, 121, 2007.

[5] G.P. Celata *et al.*, *Multiphase Science and Technology* **19-2**, 183, 2007

[6] E. Wagner *et al.*, *Journal of Heat and Mass Transfer*, **42-10**, 875, 2006.

[7] G. Duhar *et al.*, *Journal of Heat and Mass Transfer*, DOI 10.1007/s00231-007-0287-y, 2007.

[8] L. Tadrist *et al.*, *Microgravity Science and Technology* **19 (3-4)**, 130, 2007.

[9] P. Di Marco and W. Grassi, *Multiphase Science and Technology* **19-2**, 141, 2007.

[10] I.V. Roisman *et al.*, *Phys. Rev. E* **76**, 026302, 2007.

[11] T. Gambaryan-Roisman *et al.*, *Microgravity Sci. Technol.* **XIX (3/4)**, 151, 2007.