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Nucleate pool boiling in microgravity: Recent progress and future prospects

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ABSTRACT

Pool boiling on flat plates in microgravity has been studied for more than 50 years. The results of recent experiments performed in sounding rocket are presented and compared to previous results. At low heat flux, the vertical oscillatory motion of the primary bubble is responsible for the increase in the heat transfer coefficient in microgravity compared to ground experiments. The effect of a non-condensable gas on the stabilisation of the large primary bubble on the heater is pointed out. Experiments on isolated bubbles are also performed on ground and in parabolic flight. The effect of a shear flow on the bubble detachment is highlighted. A force balance model allows determining an expression of the capillary force and of the drag force acting on the bubble.

1. Introduction

Liquid vapour flows exist in a wide variety of applications in both normal gravity and reduced gravity environments. As it is usually the case, there are many benefits and drawbacks in the use of two-phase systems and, consequently, serious considerations are needed before deciding on whether or not to proceed with the design, construction and use of these systems, particularly in a reduced-gravity context.

In normal gravity, or terrestrial applications, gas–liquid flows have been traditionally studied by the petroleum and nuclear industries. The petroleum industry has focused most of their efforts on flow through long pipelines with the intent of transferring a mixture of crude oil and natural gas from the well and then performing the separation of the components or products at the refinery. The nuclear industry has been concerned with system stability and safety with the primary intent of preventing dry out of the nuclear reactor through either a heat transfer/fluid flow instability or loss of coolant accident as the heat energy is transferred from the reactor to the turbines. The chemical industries have utilised gas–liquid contactors to increase interfacial heat and mass transfers in absorption, stripping and distillation processes that involve two-phase flow though complex geometries.

In a reduced gravity environment, the principles remain the same. The applications concern the thermal management systems for satellites, the power managements systems for long time missions or manned space platforms, and fluid management from the storage tanks through the lines to the engine. Thermal management systems transfer heat from a source

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(resistance heat from electronic equipment) to a sink, typically through a radiator panel. Different devices are used depending on the power to be transferred: heat pipes, loop heat pipe, single-phase mechanical pumped loop.

Another important problem concerns fluid management: the behaviour of the propellant in the tanks of the launchers and the transfer from the tank to the engines through the supply lines. The cryogenic liquids are pressurised by their vapour or a non-condensable gas. During the different phases of the mission (propelled phase, ballistic phase) it is important to control the phase distribution and the evolution of temperature and pressure inside the reservoirs. The evolution of these parameters strongly depends on heat and mass transfers. During the ballistic phase of the mission, the tank wall is heated by solar radiation and thermal dissipation due to engine and electrical devices. Since there is no thermal convection in microgravity, the heat transfer between the heated wall and the liquid is mainly due to heat conduction, and the wall temperature can become greater than the required temperature for the onset of nucleate boiling. The study of boiling in microgravity is thus of particular interest in this situation.

However, boiling is a complex phenomenon, which combines heat and mass transfers, hydrodynamics, and interfacial phenomena. Furthermore, gravity affects the fluid dynamics and may lead to unpredictable performances of thermal management systems. It is thus necessary to perform experiments directly in (near) weightless environments. Besides the ISS, microgravity conditions can be simulated by means of a drop tower, parabolic flights on board an aircraft or a sounding rocket. Several studies on pool boiling in microgravity were performed for the last 50 years. We will focus our analysis on nucleate boiling on flat plates and also on boiling on an isolated nucleation site. Since this review is far to be exhaustive, additional information can be found in other previous reviews by Straub [1], Ohta [2], Di Marco [3,4], Kim [5].

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2. Pool boiling on flat plates in microgravity

2.1. Boiling regimes

The study of pool boiling in microgravity has begun in the 1960s with the NASA Space programme with experiments performed during short test time in drop towers by Merte and Clark [6] or Siegel [7]. During the 1980s and the 1990s, experiments on flat heated plates have been carried out during longer microgravity periods in parabolic flights, sounding rockets or aboard the space shuttle by Zell et al. [8], Lee et al. [9], Ohta [10] and Oka et al. [11], Straub [1]. These experiments have shown the existence of stable boiling regimes in microgravity over long periods. In a review of these experiments, Straub [1] remarked that gravity has a relatively weak influence on heat transfer in nucleate boiling, but it strongly affects the dry out of the heated plate, reducing significantly the critical heat flux in microgravity. These experiments were performed with different fluids, mainly refrigerants R11, R12, R113, R123, on flat plates of different sizes, at different reduced pressures, liquid subcoolings.

First, the onset of nucleate boiling appears for a lower wall superheat in microgravity compared to 1-g with an upward facing plate. In normal gravity, thermal convection cools down the heated plate and delays the onset of nucleate boiling. Then different nucleate boiling regimes are observed. In the experiments of Lee et al. [9], Ohta [10] and Oka et al. [11], one large bubble is levitating over the heated surface. It is separated from the wall by a liquid layer in which many very small bubbles are nucleated, grow and coalesce with the large bubble, which oscillates up and down due to coalescence events, but never touches the wall.

In other experiments [8], the large bubble is in contact with the wall and covers a significant part of the heated surface. Its size is controlled by heater size, wall superheat, and liquid subcooling. Other small bubbles are nucleated around the larger one and coalesce with it. This boiling regime is rather observed on small heated plates or at high heat flux. If liquid subcooling is sufficiently high, the bubble may keep a constant size on the wall, balanced by evaporation at its foot and condensation at its top. If subcooling is too low, the large bubble expands over the heated surface and a dry-out of the surface occurs. A large bubble is observed when the microgravity level is very low, in sounding rockets or space shuttle experiments. In parabolic flight, due to g-jitter, smaller bubbles are observed near the heated surface. They are detached or swept by g-jitter. A large bubble is not observed for low heat fluxes when liquid subcooling is high. Bubbles nucleate on the wall, quickly coalesce after their detachment, and sometimes even before.

The influence of pressure was studied by Straub [1], who clearly showed that in earth gravity conditions, an increase of pressure causes an increase of heat transfer. The effect of liquid subcooling on heat transfer has been studied by several authors like Lee et al. [9], Ohta [10] or Oka et al. [11]. Unfortunately, in most of these experiments, subcooling was changed by varying the pressure. It is therefore difficult to distinguish separately the effect of subcooling and pressure on the change in heat transfer. Recent experiments of Kannengieser et al. [12] with a controlled pressure showed that subcooling had no influence in the fully developed boiling regime, when the bubbles cover the whole heated plate. For low heat fluxes, heat transfer is enhanced in microgravity compared to the case of a 1-g upward facing plate and decreased compared to the case of a 1-g downward facing plate.