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Research Paper

Experimental investigation of liquid retention in a cyclone evaporator under variable gravity conditions

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HIGHLIGHTS

- A cyclone evaporator in both isothermal and non-isothermal cases has been studied.
- For 100 ml charge the fluid never left the evaporator because of the magnetic stirrer.
- V_p stability in low g decreases with increase in the rotational magnetic stirrer speed.

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ABSTRACT

For the first time a cyclone evaporator has been designed and tested with perfectly wetting liquids in two separate experiments on condensation, at variable gravity conditions during parabolic flights. Two liquids (FC-72 and HFE-7100), with surface tension coefficient of 12–15 mN/m, were used in the experiments. The concept of the liquid retention by the centrifugal force and the specific design of the walls were validated in the first series of experiments in isothermal conditions. The liquid behaviour inside the experimental cell in weightlessness is reported and discussed for the variable liquid volume (100–200 ml) inside the cell and the rotating velocity of the magnetic stirrer inside the evaporator (0–900 rpm). The data obtained during the isothermal case were used to improve the design of the evaporation cell for the non-isothermal case, tested during a second parabolic flight campaign. In this second experiment, both the power (1.8–16 W) and rotational velocity of the magnetic stirrer (0–250 rpm) were varied. For a fluid charge of 100 ml the same fluid never left the evaporator in all tests performed with rotation of the magnetic stirrer. The vapour pressure in the cell increased during microgravity period. It was found that the stabilization of vapour pressure after transition to microgravity decreases with an increase in the rotational speed of the magnetic stirrer. We conclude that the cyclone evaporator is also an ideal candidate for those systems that have to work in microgravity and rely on pool boiling, because the cyclone chops large bubbles that would otherwise occupy the whole evaporator space and reduce the heat-transfer rate.

1. Introduction

Evaporators are employed in a variety of engineering processes, from food and beverage, to pharmaceutical, chemical plants and paper production, to mention just a few. The choice of the actual evaporator design depends on the liquid used, the working conditions, and the quality of the output desired. In-tube evaporators are widely used in scientific experiments [1,2] to vaporize liquids that then are used for controlled experiments, such as in-tube convective condensation. In these cases, hot water or steam is circulated inside a jacket around an inner tube, and the liquid to be vaporized is circulated inside the inner tube. At times, to improve the heat-transfer rate, baffles are also implemented in the jacket.

Industrial plate heat-exchanger evaporators have been tested in Huang et al. [3], in terms of heat-transfer coefficient and pressure drop with chevron angles of 28°/28°, 28°/60° and 60°/60°, with R134a and R507A as refrigerants. The tests revealed nucleate boiling as the heat-transfer mechanism and a strong dependence on the heat-transfer coefficient from the heat flux, but a weak dependence on the refrigerant mass flux, the vapour quality and the chevron angle. In contrast, the refrigerant frictional pressure drop showed a very strong dependence on mass flux and vapour quality, and also increased with higher chevron angles.

A triangular microgroove etched silicon evaporator was developed and tested by Tsukamoto and Imai [4]. The indium tin oxide heating element is deposited on the back side of the silicon wafer. The system is composed of an evaporator, condenser, pump, accu-

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mulator and flow meter. The maximum heat flux achieved with water as the working fluid and a flow rate of 1 ml/min is 146 W/cm^2. The measured pressure drop of the evaporator is around 1000 Pa.

The recently renewed interest in space exploration has driven more fundamental studies to guide the design of more powerful and lighter heat-transfer devices that will take mankind to Mars and beyond. Heat-transfer devices that rely on a single phase have limitations in terms of energy to be transferred per unit volume, weight and volume. As pointed out by Konishi et al. [5], a naturally important improvement is to consider two-phase heat transfer such as boiling and condensation. During multiphase flow with phase change: a) large amounts of heat are transferred (latent heat instead of sensible heat typical of single phase); b) lower temperature temperatures are dictated by a phase change at that specific operating pressure; c) and because a smaller quantity of working fluid is needed, the volume and weight of the cooling system are less. The problem with boiling and condensation is that these heat-transfer modes are less predictable, and despite good efforts made over the last few decades, there are no general design rules to size a system based on them. The large variety of flow regimes and governing parameters makes it very difficult to develop even tools such as Computational Fluid Dynamics codes that would help the designer to predict the overall behaviour of a system before any hardware is built and tested.

There are different platforms with which to perform tests in microgravity, as also reported in Konishi and Mudawar [6]. There are drop towers, which provide a few seconds of high-quality microgravity, and parabolic flights, where typically there are around 20 s of microgravity, but the microgravity quality is somehow hampered by the pilot's skills and the weather. Sounding rockets provide much longer microgravity periods, typically up to 10–13 minutes of good microgravity quality. And ultimately, the International Space Station provide weeks of continuous testing at very low microgravity levels. Going from drop towers to space stations, the complexity and time needed for the preparation for an experiment increases hyperbolically, and the cost also increases considerably. Of these microgravity platforms, parabolic flights give the opportunity for the experimenters to be close to the test rig, so much larger test rigs are allowed and many parabolas (typically around 30 each day) can be performed over 3 days. Finally, different experimental settings can be investigated, resulting in a much richer set of results.

The behaviour of a liquid undergoing phase change in microgravity is completely different from that found on earth. For this reason experiments in reduced gravity must be performed to ascertain the performance of phase-change devices, such as evaporators and condensers. A pool-boiling experiment conducted by NASA (Lee et al. [7]), using R-113 and flat heaters, demonstrated the heat-transfer coefficient in enhanced microgravity with respect to that on earth. Lee et al.'s [7] argument is that flat surface heaters produce an enhancement in nucleate boiling heat transfer, and wire heating should not produce appreciable changes in nucleate boiling heat transfer. Pool boiling in microgravity suffers from the fact that the bubble growing at the top of the heater tends to occupy the whole volume available, and it becomes difficult to displace it. This leads to reduced heat-transfer rates and performance. To overcome these limitations, a number of experiments have been done on flow boiling in microgravity, which helps to remove the microbubbles from the heater. Konishi et al. [5] investigated the flow boiling of FC-72 in up-flow inside a rectangular channel of a 2.5×5 mm section, and over a 500 mm length, where both single-sided and double-sided heater configurations were implemented, with visualization done on the remaining transparent sides of the channel. Konishi et al. [5] reported a reduction of flow boiling heat transfer with reduced gravity and an enhancement during hypergravity periods. The authors also reported that for same inlet velocity and heat flux, double-sided heating produces a higher heat transfer than single-sided, and the authors attribute this experimental finding to higher vapour production that produces more vigorous fluid motion. A flow boiling experiment of water at nearly atmospheric pressure was carried out by Ohta et al. [8]. The evaporator channel was 150 mm long, 30 mm wide and the height varied between 2 and 5 mm. The measured Critical Heat Flux for an inlet velocity of 0.2 m/s was around 2.2 MW/m^2, which is almost 1.5 times that without additional liquid supply with the same inlet conditions. Narcy et al. [9] carried out two parabolic flights on flow boiling, using HFE-7000 flowing at mass fluxes between 100 and 1200 kg/(m^{2}s^1) up-flow, inside a sapphire transparent tube of 6 mm internal diameter and 200 mm length. The sapphire tube was coated with a transparent ITO, which provides a heat flux of 4.5 W/cm^2, and flow visualization is performed with the use of a high-speed camera. Two 'home-made' void fraction probes are also implemented at the inlet and outlet of the test section. Narcy et al. [9] concluded that the change of gravity level had little impact on the flow for mass fluxes above 400 kg/(m^{2}s^1), regardless of the flow pattern. They also stated that in the annular flow regime, the film thickness was lower in microgravity, and they speculated that this is explained by the momentum balance equation for the liquid film. In contrast, the same authors found that the heat-transfer coefficient is similar in normal and reduced gravity, and argued that this is due to the low dependency of the model from the liquid thickness and the fact that the heat-transfer coefficient is mainly dependent on the wall shear stress that is similar in normal and reduced gravity. Luciani et al. [10] reported on boiling heat transfer inside a vertical microchannel of hydraulic diameters 0.48, 0.84 and 1.18 mm, 50 mm length, using HFE-7100. They used wire heaters and performed visualization. They found that the heat-transfer coefficient is more than 30% higher in microgravity than normal gravity, and is higher at microchannel inlet, probably because of entrance effects. The authors did not find any appreciable difference in heat-transfer coefficient between normal and hypergravity conditions.

Various methods to prevent the liquid spilling in microgravity are proposed in the literature. All methods can be split in two groups [11]: active and passive ones. The active methods are based on the implementation of external forces to the liquid: electrical field; accelerations etc. However, they require a continuous supply of energy to keep the system running. All passive methods are based on wetting and the free surface properties of fluids [12,13]. For example, inserts of special shape can be placed into the reservoir, or the internal walls of a tank are partially covered with wetting/un-wetting coating. Another approach is the creation of a surface relief surrounding the area where liquids need to be contained. Detailed description of working principle of the barrier can be found in [13].

In this paper we investigate in microgravity a novel design of a cyclone evaporator, which provided vapour for a condensation test rig. The condensation tests performed in microgravity through a parabolic flight are reported in two recent papers [14,15]. The cyclone evaporator is a cylindrical chamber inside which HFE-7100 or FC-72 is heated by an electric heater positioned on the cylindrical bottom face. Inside the cylindrical chamber a magnetic stirrer is implemented, to make sure that during microgravity, for a certain quantity of the working fluid, it does not exit the top opening, and the vapour bubbles are continuously chopped, thus avoiding that a big bubble occupies the whole chamber and gets stuck, with detrimental effects on heat transfer.

2. Experimental apparatus

The present work was performed in the framework of preparations for the experiment on condensation on a curvilinear surface under weightlessness conditions, during two separate parabolic flights funded by the European Space Agency. A detailed description of the condensation experiment concept can be found in [14,15].