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Experimental study on pool boiling of distilled water and HFE7500 fluid under microgravity

Yan-jie Yang, Xiao-qian Chen *, Yi-yong Huang, Guang-yu Li

College of Aerospace Science and Engineering, National University of Defense Technology, Changsha, 410073, PR China

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ABSTRACT

The experimental study on bubble behavior and heat transfer of pool boiling for distilled water and HFE7500 fluid under microgravity has been conducted by using drop tower in the National Microgravity Laboratory of China (NMLC). Two MCH ceramic plates of 20 mm(L) × 10 mm(W) × 1.2 mm(H) were used as the heaters. The nucleate boiling evolution under microgravity was observed during the experiment. It has been found that at the same heat flux, the bubbles of HFE7500 (which has smaller contact angle) grew faster and bigger, moved quickly on the heater surface, and were easier to merge into a central big bubble with other bubbles than that of distilled water. The whole process of bubbles coalescence from seven to one was recorded by using video camera. For distilled water (with bigger contact angle), the bubbles tended to keep at the nucleate location on heater surface, and the central big bubble evolved at its nucleate cite by absorbing smaller bubbles nearby. Compared with the bubbles under normal gravity, bubble radius of distilled water under microgravity was about 1.4 times bigger and of HFE7500 was about more than 6 times bigger till the end of experiment. At the beginning, pool boiling heat transfer of distilled water was advanced and then impeded under microgravity. As to HFE7500, the pool boiling impedes the heat transfer from heater to liquid under microgravity throughout the experiment.

1. Introduction

Boiling in microgravity has become an increasing significant subject for investigation, since for space applications boiling is a preferable mode of heat transfer [1–5]. Applications of boiling heat transfer in microgravity environments can be found in thermal management, on-orbit storage and supply system for cryogenic propellants and life-support fluids, power conversion system, fluid handling and control, electronics cooling, etc. A number of experiments have been conducted to confirm whether boiling is an appropriate mechanism of heat transfer for space applications and how bubble dynamics behaves without the influence of buoyancy under microgravity by using various facilities and carrier systems like drop tower, parabolic flight trajectories, Space Shuttle and space station [1–9].

Zhao [6] achieved 3 different diameters at which bubble detached from the heating platinum wire under microgravity. However, the bubble movement on horizontal plane in two axes cannot be observed but only alone the wire. Warrier and Dhir [7] applied a designed wafer settled with series of tiny heaters (five cavities were settled) and twelve thermistors. They studied the heat transfer at heater surface with different superheating and subcooling. They reported that at low superheating bubbles generated on heater surface slided and merged to yield a large bubble located in the middle of the heater, and at high superheating the large bubble may lift off from the heater but continued to hover near the heater. They also pointed out that any correlations that are developed for nucleate boiling heat transfer under microgravity condition must account for the existence of vapor escape path from the heater, relative size of the large bubble and heater, and the size and geometry of the chamber used.

Ohta and Baba [8] also reviewed the experiments under microgravity highlighting the micro layer underneath the bubble and its observation tools. The planned experiments on board the international space station is introduced in their works. Henry and Kim [9] studied the effect of heater size on pool boiling heat transfer under microgravity with KC-135 aircraft. They mentioned satellite bubbles around the primary bubble were the mechanism by which CHF (Critical Heat Flux) occurred in low-g for larger heaters. They observed the bubble coalescence but did not study the effect of liquid contact angle on bubble movement and coalescence. For liquid with small contact angle it is possible to be combined with one another on the moving path as its small contact force at the same temperature gradient, not necessary to be combined with the primary bubble. Cecere [10] studied self-rewetting fluids for heat transfer in

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* Corresponding author.

E-mail addresses: yanjie_young@sina.com (Y.-j. Yang), chenxiaoqian@nudt.edu.cn (X.-q. Chen), yiyong_h@sina.com (Y.-y. Huang), lgynudt@sina.com (G.-y. Li).

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microgravity and pointed that compared to ordinary fluids, self-rewetting fluids have better thermal performance. Besides, he defined the architecture of flight payload to the application of heat pipes filled with self-rewetting fluids.

On the bubble growth mechanism and boiling heat transfer, researchers did inspiring works. On normal gravity, Ivashniov and Smirnov [11] studied the “slow wave” of hot water depressurization and found that the depressurization boiling was not uniform but happened from the open end deep into the vessel. They built a model considering the difference in phase velocities which would induce bubble breakup. They further researched the interface model of phase transfer and built two models: a “rigid” sphere for no-slip condition and “soft sphere” for slip condition [12]. Based on these two models they obtained an approximate dependence of heat flux and bubble interface as a function of the Jacob and Péclet. They convinced their models with experimental data as “rigid” sphere for small radius and “soft” sphere for radius greater than critical size. They suggested that there was first and second self-similarities for the motion of “soft” growing bubble. They did not modify their models for motionless bubbles and for moving bubbles of constant size.

Kim, Benton and Kucner [13] studied subcooled pool boiling heat transfer under microgravity using 3 M Fluorinert FC72 (electronic liquid) with the Terrier-Improved Orion sounding rocket. They reported that at wall superheat below 25 °C the effect of gravity was little on boiling heat transfer. The primary bubble was the results of coalescence of small bubbles and remained constant in size for a given superheat. They also reported the way to define whether dry out occurred by the temperature increase. Scholars did work on boiling heat transfer and reviewed the boiling experiment under microgravity and the history [14].

Kannegieser, Colin and Bergez [15] researched the effect of different reservoir pressures and wall heat fluxes on pool boiling using HFE7000 fluid with the Sounding Rocket Maser 11. They observed the strong effect of Marangoni convection and analyzed the heat transfer as a function of the relative values of both wall temperature and saturation temperature. Kubota, Kawanami, et al. [16] investigated the gravity effects on the micro layer behaviors and corresponding local heat transfer coefficients using a transparent heater at the ESA parabolic flight campaign. They introduced that the residual gravity has a strong effect on liquid-vapor behaviors. They also observed the liquid-vapor behavior and its effect on heat transfer.

Boiling is a complex process which is affected by heater surface, heat flux, pressure, liquid physical characteristics, etc. There is only a partial and in some aspects contradictory knowledge of microgravity boiling have been attained so far.

In this paper, five experiments have been conducted to better understand bubble dynamics of different contact angle under microgravity in National Microgravity Laboratory of China (NMLC). Series of experiments were designed to be compared in working liquid, volume of liquid, heater power (or heat flux) and heater pose to study the effect of microgravity and contact angle on bubble dynamics and heat transfer.

Bubble nucleation was analyzed as was very important to determine the boiling onset and the highest heat transfer coefficient compared with transition boiling and film boiling under microgravity. Bubble dynamics of growth, migration, coalescence and lift off were also need to be analyzed as they influenced heat transfer obviously by heat and mass transfer and disturbing the week convection flow under microgravity. Then heat transfer change of different working liquid under microgravity was compared in order to study the contact angle effect on heat transfer under microgravity. Last, bubble coalescence and migration were compared of different working liquid to better understand the effect of contact angle on bubble dynamics.

2. Experiment facility, apparatus and procedure

Five experiments were designed and the detailed arrangement is listed in Table 1. From round 1 and 2 the effect of liquid volume can be studied. Different working liquid have effect on boiling heat transfer and bubble dynamics by comparing the experimental results of round 2 and 3. Heater power was studied by setting round 3, 4 and 5 with 57 W (14.25 kW/m^2), 22 W (5.5 kW/m^2) and 94 W (23.5 kW/m^2). As the very short time of microgravity the effect of residual gravity should be concerned. In each round heater pose was different by setting two ceramic heating plate to study the effect of residual gravity direction on heat transfer and bubble dynamics.

Table 1
The test matrix and experiment arrangement.

Round$^{\#}$	Working liquid	Volume of liquid	Heater power	Heater pose
1	Distilled water	50%	57 W, 57 W	side, forth
2	Distilled water	90%	57 W, 57 W	side, forth
3	HFE7500	90%	57 W, 57 W	side, forth
4	HFE7500	90%	22 W, 22 W	athwart, forth
5	HFE7500	90%	22 W, 94 W	athwart, forth

2.1. Experiment facility – NMLC

The height of the NMLC drop tower is 116 m and the outer diameter is 12 m. The microgravity level of two cabin assembling is about 10^{-5} g_0 with duration of about 3.6 s.

Fig. 1 a shows the schematic of two-cabin drop tower. The vacuum between two cabins is below 30 Pa. The inner cabin is hanged on the roof of outer cabin, both cabins are hanged by magnetic lock. Once shuttled down, the magnetic lock unlocks and two cabins start dropping synchronously. As the resistance of air the out cabin will drop slower than inner cabin and the distance of 0.8 m is designed according to the pursuing time. The recycle net begins to work when outer cabin falls into the net. The maximum impact acceleration of recycle net should be lower than 20 g. The recycle barrier is made of many tyres in case the recycle net breaks and the cabins fall to the ground. Fig. 1(b)–(d) show the whole view of drop tower, inner cabin and outer cabin.

2.2. Experiment apparatus and the payload

To study the effect of surface tension on bubble dynamics, 3 M Fluorinert HFE7500 and distilled water were used as the working liquid. 3 M Fluorinert HFE7500 is an electronic fluid widely used in electronic industry with low surface tension. Distilled water has medial surface tension on ceramic wall. Part physical parameter of the working liquid is listed in Table 2. All physical parameters are the values of 25 °C.

The static contact angle of working liquid on heater surface is measured by a Contact Angle Meter (SL-200B, Shanghai Suolun Co. Ltd) with a 5 μ L (microliter) droplet. Fig. 2 shows the first test of contact angle of HFE7500 (left) and distilled water (right) on the plate center. HFE7500 spreads on the surface completely and was defined as 0° contact angle. Distilled water with left and right contact angle 58° is averaged 58°. Contact angle was tested at four corners of plate for each working liquid. 5 measurements of each working liquid are averaged and the mean value is listed in Table 1. The uncertainty in the measured contact angle is estimated to be ±1°.

Schematic of the experimental payload is shown in Table 3 and Fig. 3 shows the experiment setup.

Microgravity level was measured and recorded by accelerometer settled in the test cabin and transferred to data acquisition system along with other signals of temperature and pressure at the same time. The test matrix is shown in Table 1.

2.3. Process of experiment

Before the experiment, some operations are necessary to be conducted. The experiment payloads are assembled in inner cabin firstly and then are locked in outer cabin (double cabin assembling). The evacuation