Pool Boiling Heat Transfer in Microgravity

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Abstract

The pool boiling heat transfer of FC-72 on a plain plate with a heating area of 15*15 mm^2 in different pressure and subcooling has been studied experimentally both in normal gravity on the ground and in microgravity aboard the Chinese recoverable satellite SJ-8. A quasi-steady heating method is adopted, in which the heating voltage is controlled as an exponential function with time. Three modes of heat transfer, namely single-phase natural convection, nucleate boiling, and transition boiling, are observed, while the nucleate pool boiling are the major subject for discussion in the present paper. In normal gravity, the present data is compared with those obtained by other researchers, and a satisfactory agreement is evident and warrants reasonable confidence in the data. Compared with terrestrial experiments, the boiling curves in microgravity are considerably gentle, and CHF is no more than 40% of that in terrestrial condition. In microgravity, influences on boiling curves of the pressure and subcooling are similar with those in normal gravity, namely that the heat transfer coefficient and CHF will increase with subcooling for the same pressure, and that they will also increase with pressure for the same subcooling.

Keywords: microgravity, pool boiling, subcooling, plate heater

1. Introduction

Pool boiling in microgravity has become an increasing significant subject for investigation, since many potential applications exist in space and in planetary neighbors due to its high efficiency. However, the investigation in microgravity suffers for unique and stringent constraints in terms of size, power and weight of experimental apparatuses, and of number and duration of the experiments. Thus, only a partial and in some aspects contradictory knowledge of microgravity boiling has been attained so far. On the progress in this field, several comprehensive reviews are available. For example, Straub [1] issued a comprehensive review of his own activity on this field from the early 1980s to date, while Di Marco [2], Kim [3], and Ohta [4] recently issued reviews of microgravity boiling researches in Europe, in US, and in Japan, respectively.

Boiling is a very complex and illusive process because of the interrelation of numerous factors and effects as the nucleate process, the growth of the bubbles, the interaction between the heater's surface with liquid and vapor, the evaporation process at the liquid-vapor interface, and the transport process of vapor and hot liquid away from the heater's surface. For a variety of reasons, fewer studies have focused on the physics of the boiling process than have been tailored to fit the needs of engineering endeavors. As a result, the literature has been flooded with the correlations involving several adjustable, empirical parameters. These correlations can provide quick input to design, performance, and safety issues and hence are attractive on a short-term basis. However, the usefulness of the correlations diminishes very quickly as parameters of interest start to fall outside the range of physical parameters for which the correlations were developed. Thus, the physics of the boiling process itself is not properly understood yet, and is poorly represented in the most correlations, despite of almost seven decades of boiling research.

The present work is a research effort on pool boiling heat transfer both in normal gravity on Earth and in microgravity aboard the Chinese recoverable satellite SJ-8. The results of the experiments in normal gravity before the flight experiment were also presented in the present paper, which were compared with those in microgravity.

2. Experimental Facility and Procedure

The plane plate heater has an Al_2O_3 ceramic substrate embedded in PTFE base with a size of 28×20×1 mm^3. The effective heating area is covered by a multi-layer alloy film with an area of 15×15 mm^2 and a thickness about 10 μm. The film, shown in **Fig. 1**, is comprised with several metals (Cu, Au, Ni, Cr). Its nominal resistance is 6 Ω. It is also used as thermometer to measure the averaged temperature of the heater surface in the experiments. **Fig. 2** shows the roughness of the heater surface. The electric current through the heater is measured by a Hall transducer. Its output and the

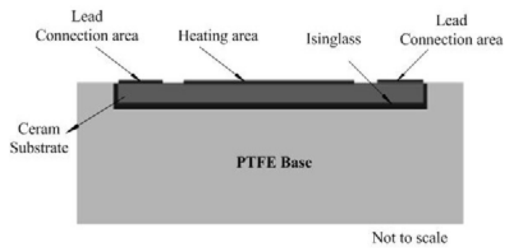


Fig. 1 The heater structure

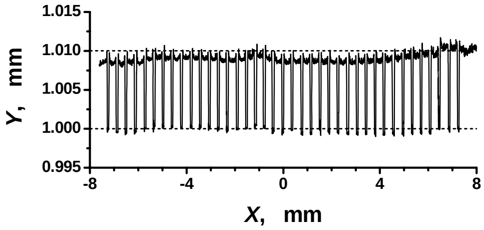


Fig. 2 The roughness of the heater surface.

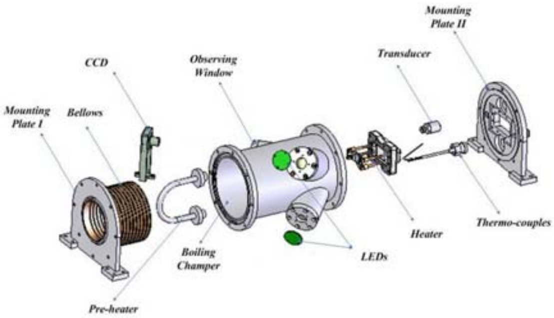


Fig. 3 The boiling chamber and its accessories

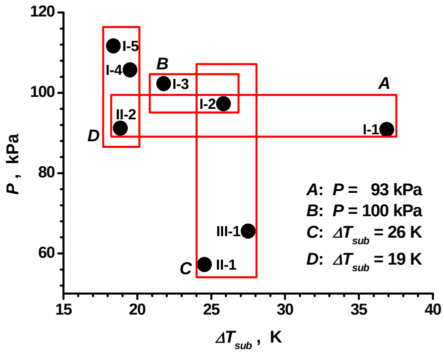
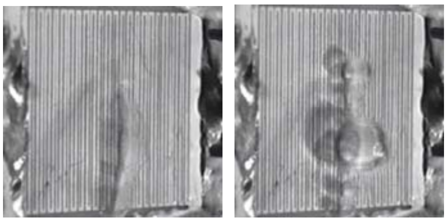
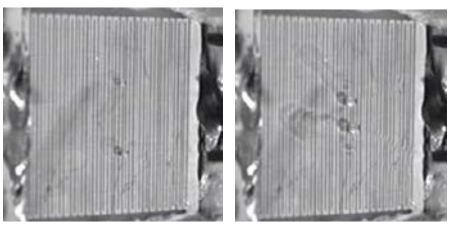


Fig. 4 Experimental conditions in space flight.



(a) Explosive boiling in the first run



(b) Bubbles grow gradually in the second run

Fig. 5 The onset of boiling in the first stage of the space experiments.

voltages across the heater are sampled at a rate of 400 Hz, but a smaller storage rate of 100 Hz is used after 4-point averaging of the initial data.

The boiling chamber (**Fig. 3**) is filled with about 1700 ml of degassed FC-72, and fixed inside an air-proof container in which the pressure is initially about 100 kPa. A bellows connected with the chamber will allow the pressure in the chamber to be approximately constant. The absolute pressure within the boiling chamber is measured using a pressure transducer with a range of 0~0.2 MPa and an uncertainty of 0.25%FS (full scale).

An auxiliary heater is used for adjusting the temperature of the bulk liquid from the ambient temperature to about half of the saturation temperature under the corresponding pressure. Two thermocouples with a range of 0~100 ^{o}C and an uncertainty of 0.5 ^{o}C are used to measure the bulk temperature of the fluid in the boiling chamber. The outputs are sampled at rate of 1 Hz.

A CCD video camera is used to obtain images of the motion of vapor bubble or film around the heater, which is digitized and recorded at a speed of 25 fps in MPEG. Four LEDs (light-emitting diode) are used to light the boiling chamber through two optical windows.

A quasi-steady heating method is adopted, in which the heating voltage is controlled as an exponential function with time, namely

$$U=U_0 e^{\tau/\tau_0} \qquad (1)$$

where τ denotes the heating time. In order to make the heating process as a quasi-steady state, the parameter τ_0 is set for 80 s, which satisfies the quasi-steady heating condition [5].

The whole space experiments are designed as two stages. Both of them include different groups of runs which consist of pre-heating, stabilizing and boiling phases. The first stage is conducted in an ambient pressure condition with the initial pressure of about 100 kPa. After the first stage has been performed, a solenoid valve is opened to vent air from the container to the module of the satellite, and then the pressure inside the container was reduced to the same of that in the module of the satellite, namely 40~60 kPa. Thus, in the second stage of the space experiment, the pressure in the boiling chamber is different from those in the first stage. One more stage is added in actual flight, which is also performed in the reduced pressure condition.

3. Results and Discussions

There are 8 runs obtained in the space experiment. The experimental conditions are shown in **Fig. 4**, which can be classified into four groups according to different pressure and/or subcooling.

Because of the residual gravity which is estimated in the range of 10^{-3}~10^{-5} g_0, there could be a week single-phase natural convection before the onset of boiling. In the 5 runs of the first stage, the first appearance of bubbles is observed at 20.89 s, 7.68 s, 7.12 s, 3.54 s, and 3.84 s, respectively. In the first run, the first

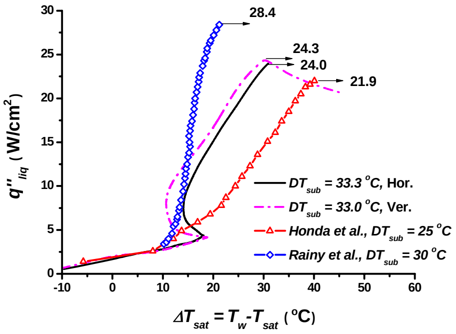


Fig. 6 Boiling curves in normal gravity.

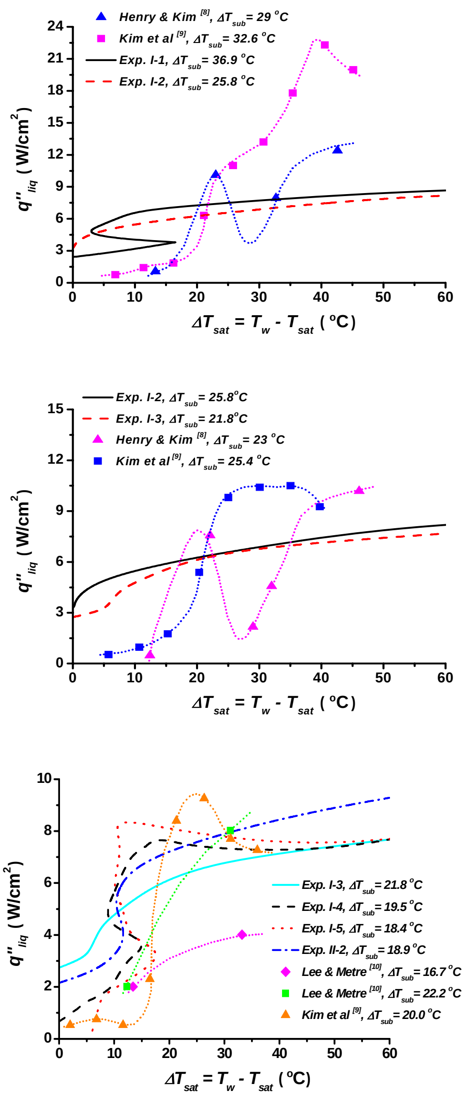


Fig. 7 Comparisons of the present data in microgravity with those obtained by others.

appearance of bubbles is abrupt and explosive (**Fig. 5**a), and an obvious over-shooting is observed in the history of the heater temperature, correspondingly. In the follow-up runs, the bubble is observed to grow slowly after their first appearance (**Fig. 5**b). The processes are even at an obvious standstill. Correspondingly, no over-shooting can be observed in the history of the heater temperature. Comparing with the first runs, the nucleate boiling occurred significantly earlier in the follow-up runs. Considering the experimental procedure, it may indicate that there could be residual micro-bubbles in cavities after the preceding runs. These micro-bubbles would make the cavities easier to be activated, thus, the boiling will begin at a lower wall superheat temperature of the heating surface.

Fig. 6 shows the results of the control experiments performed on the ground before the space flight, which comparing with those of Rainy et al.[6] and Honda et al.[7] The agreement is satisfactory, which warrants reasonable confidence in the data.In **Fig. 7**, the present data in microgravity are compared with those obtained by other researchers. Taking into account of differences in the structure of heaters, pressure, subcooling, working fluid, and so on, the agreement is fairly good.

Fig. 8 shows the boiling curves at different pressure and/or subcooling in microgravity. It's shown that the nucleate boiling curve will be left-shifted with the increase of subcooling for the same pressure. For the same subcooling, the boiling curve will be left-shifted with the increase of pressure. CHF will also increase with the subcooling and/or pressure. The above characteristics are similar with the results obtained on Earth.

In **Fig. 9**, the boiling curves in microgravity are compared with the control experimental result in normal gravity. The boiling curves in microgravity are considerably gentle, and even have no turning point, which causes some difficulties in determining accurately the occurrence of CHF. For the same pressure, nucleate wall superheat in microgravity. CHF is also quite lower in microgravity, which is no more than 40% of that in terrestrial condition.

4. Conclusions

In the present paper, the pool boiling heat transfer of FC-72 on a plain plate in different pressure and subcooling has been studied experimentally both in normal gravity on earth and in microgravity aboard the Chinese recoverable satellite SJ-8 using a quasi-steady heating method.

It's shown that the nucleate boiling curve will be left-shifted with the increase of subcooling for the same pressure. For the same subcooling, the boiling curve will be left-shifted with the increase of pressure. CHF will also increase with the subcooling and/or pressure in microgravity. The above characteristics are similar with the results obtained on Earth. Compared with terrestrial experiments, the boiling curves in microgravity are considerably gentle, and even have no turning point, which causes some difficulties in determining accurately the occurrence of CHF. For the same pressure, nucleate boiling occurred significantly earlier with a quite lower

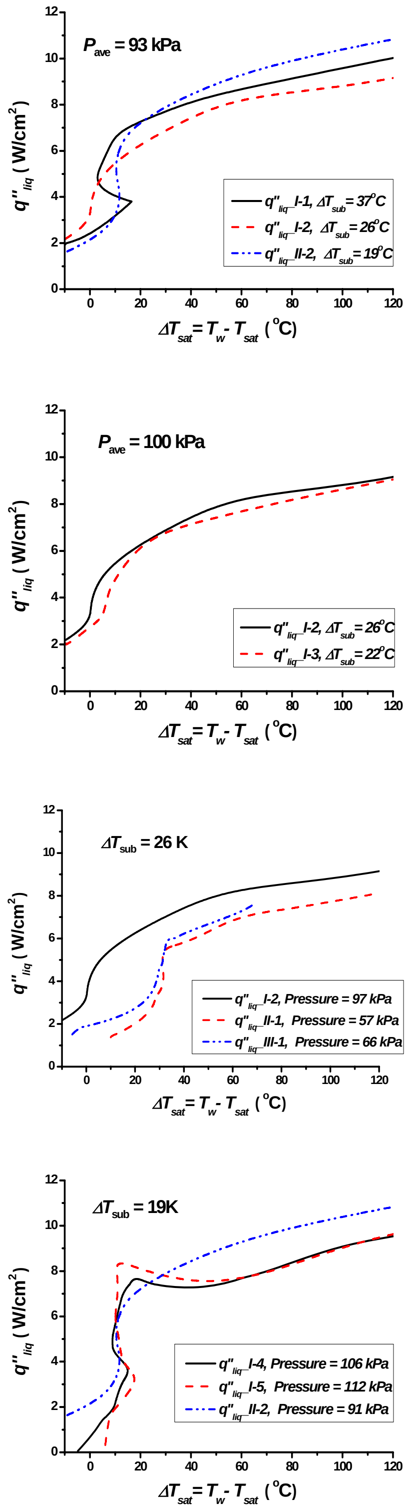


Fig. 8 Boiling curves at different pressure and/or subcooling in microgravity.

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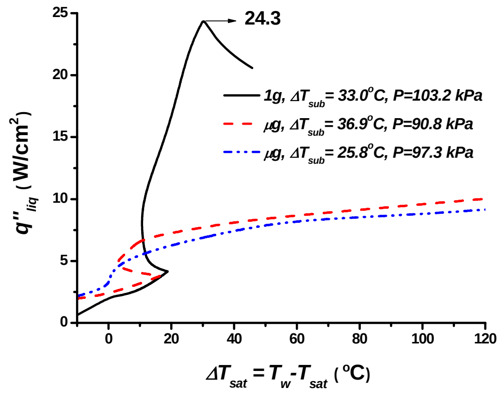

Fig. 9 Comparison of boiling curves in different gravity.

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