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Experimental study of subcooled flow boiling heat transfer on micro-pin-finned surfaces in short-term microgravity

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ABSTRACT

The flow boiling heat transfer of subcooled air-dissolved FC-72 on micro-pin-finned surfaces was studied in microgravity by utilizing the drop tower facility in Beijing. The micro-pin-fins with the dimension of $30 \times 30 \times 60\,\mu m^3$ (width × thickness × height), named PF30-60, were fabricated on a silicon chip by using the dry etching technique. For comparison, experiments of flow boiling heat transfer in terrestrial gravity were also conducted. The effects of inlet velocity on both flow boiling heat transfer and bubble behavior were explored. It was found that gravity has nearly no effect on flow boiling heat transfer for the departure of the inertial-force-dominant bubbles in the low and moderate heat fluxes regions. In contrast, in the high-heat-flux region, the flow boiling heat transfer deteriorates and the critical heat flux (CHF) decreases due to the bubble accumulation in the channel. For PF30-60 at $V = 0.5$ m/s, the CHF point can be inferred to be between 20.8 and 24.5 W/cm^2, which is 63.0–74.2% of that in normal gravity. Regarding PF30-60 at $V = 1.0$ m/s, the CHF point can be inferred to be between 25.4 and 31.6 W/cm^2, which is 67.6–84.0% of that in normal gravity. The impact of gravity on CHF is closely linked to the channel geometry parameter and surface modification. The dimensionless numbers, *Ch* (Channel number) and *Sf* (Surface number), were proposed to describe the effect of the channel geometry and surface modification on the ratio of CHF in microgravity to that in normal gravity ($CHF_{\mu g}/CHF_{1g}$). An empirical correlation based on *We* (Weber number), *Ch* and *Sf* was proposed to predict the value of $CHF_{\mu g}/CHF_{1g}$ ratio in good agreement with the experimental data. This study provides a new perspective to determine the threshold inlet velocity of inertial-force-dominant flow boiling under different experimental conditions at different gravity levels.

1. Introduction

The thermal management system in aerospace equipment, especially for the microelectronic device heat dissipation, requires the cooling system to be efficient and compact in its structure, and consume a low amount of energy. Phase change heat transfer with high heat flux, small heat dissipation area, and low working temperature, is a very efficient method compared with the single-phase heat transfer. Until now, many experimental studies on passive technologies, such as mixture fluid [1], nanofluids [2–5], surface modification [6,7], and simulation work [8] in relation to passive technologies have been performed to enhance pool boiling heat transfer. Meanwhile, pool boiling in different gravity conditions has been investigated in the last decade by numerous researchers [9–15], and there are many review papers regarding pool boiling in microgravity [16–20].

As is known, flow boiling can be a practical and effective method to prevent the formation of massive bubbles by liquid inertia to flush discrete bubbles away from the heated wall and sustain liquid replenishment of the heated wall. However, the flow boiling and vapor-liquid two-phase flow involve much more complicated mechanisms than that of the pool boiling, and only a few reports on flow boiling heat transfer in microgravity are available [21].

In previous studies over last several decades, the bubble dynamics and two-phase flow characteristics at low inlet velocities were the main aspects considered. Ma and Chung [22,23] studied the bubble dynamics of flow boiling in microgravity at the inlet velocity $V = 0$–0.3 m/s, and found that the bubble departure diameter deceases with increasing inlet velocity, indicating the influence of gravity level diminishes with increasing inlet velocity. The results of Saito et al. [24] indicated that the bubbles are difficult to detach from the heater, and merge to form much

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Nomenclature

b	width of heater (mm)
Bo	Boiling number, $Bo = q/Gh_{fg}$
Ch	channel number
c_{pl}	specific heat capacity of liquid, $J \cdot kg^{-1} \cdot K^{-1}$
CHF	critical heat flux (W/cm^2)
D_h	hydraulic diameter (mm)
Eo	Eötvös number
g	gravitational acceleration (m/s^2)
g_0, $1g$	earth gravity level (m/s^2)
G	mass velocity (kg/m^2·s)
h	channel height (mm)
h_v	heat transfer coefficient, $W \cdot m^{-2} \cdot K^{-1}$
h_{fg}	latent heat of evaporation, kJ/kg
I_H	heating current (A)
K	$CHF_{\mu g}/CHF_{1g}$ of pool boiling
L	length of heater (mm)
L_c	capillary length (mm)
Nu	Nusselt number, $Nu = h_v D_h/\lambda_l$
p_h	heated perimeter (mm)
p_w	wetted perimeter (mm)
q	heat flux (W/cm^2)
Q_v	volume flow rate (m^3/s)
R_1, R_2	resistance (kΩ)
Re	Reynolds number, $Re = \rho_l V D_h/\mu$
Sf	surface number
t	time (s)
T_1, T_2, T_3, T_4	wall temperatures (°C)
T_a	average wall temperature (°C)
T_f	liquid temperature (°C)
T_{sat}	saturation temperature (°C)
U_H	heating voltage (V)
V	inlet liquid velocities (m/s)
w	width of channel (mm)
We	Weber number
ΔP	pressure drop (kPa)
ΔT_{sat}	wall superheat $= T_w - T_{sat}$ (K)
ΔT_{sub}	fluid subcooling $= T_{sat} - T_b$ (K)
μg	gravitational acceleration in microgravity (m/s^2)

Greek symbol

μ	dynamic viscosity, $N \cdot s \cdot m^{-2}$
λ_l	thermal conductivity of liquid, $W \cdot m^{-1} \cdot K^{-1}$
ρ_l	liquid density, $kg \cdot m^{-3}$
ρ_g	vapor density, $kg \cdot m^{-3}$
σ	surface tension (N/m)

larger bubbles along the heater rod in microgravity. The influence of the gravity level became more remarkable under the conditions at lower inlet fluid velocity, higher heat flux and lower inlet fluid subcooling. The two-phase flow pattern in a circular tube at microgravity level, including bubbly flow, slug flow and annular flow, is simpler than that in normal gravity in the absence of buoyancy. Celata et al. [25] studied the flow patterns in pipe flow boiling under microgravity conditions, and observed two typical flow patterns, bubbly flow, and intermittent flow. Narcy et al. [26] investigated forced convective boiling and vapor-liquid two-phase flow pattern at different gravity levels. The authors observed annular flow, slug flow and bubbly flow, and found that the gravity level has little impact on the flow for mass velocity larger than 400 kg/m^2·s regardless of the flow pattern. Zhao et al. [27,28] experimentally investigated two-phase gas-liquid flow. They proposed and modified the semi-theoretical Weber number model to improve the accuracy of prediction of the slug-to-annular flow transition of gas-liquid two-phase flow in microgravity.

Obviously, the absence of gravity deteriorates the performance of flow boiling heat transfer, because the bubble departure becomes more difficult and the bubble emerging phenomenon becomes much more dramatically. Regarding the heat transfer coefficient at low and moderate heat fluxes in microgravity, there is a disagreement among different experiments. Baltis et al. [29] found that the heat transfer performance is enhanced at low mass velocity in microgravity compared with that of in normal gravity, and that this tendency becomes less obvious with increasing mass velocity. The results of Luciani et al. [30,31] indicated that the flow boiling heat transfer coefficient in a minichannel is enhanced in microgravity. In contrast, Ohta [32] and Ma and Chung [33] found that the heat transfer coefficient is decreased in microgravity. However, instead of the disagreement in heat transfer coefficient, the influence of gravity is definitely weakened with increasing mass velocity. Therefore, it is very important for space instruments to find the threshold of velocity at different gravity levels.

The critical heat flux (CHF) is also an important parameter for boiling heat transfer to prevent the burnout of electronic devices. Ohta [32] obtained limited flow boiling critical heat flux data in microgravity at high inlet quality, but noted that they could not measure CHF accurately in the absence of local wall temperature measurements along the heated wall. Ma and Chung [33] investigated the subcooled flow boiling of FC-72 across a heated 0.254 mm platinum wire by a 2.1 s drop tower. They found that the CHFs significantly decline in microgravtiy. However, the differences in both the heat transfer rate and CHF between microgravity and normal gravity decrease with increasing flow rate. Zhang et al. [34] tested a series of CHFs at different inlet liquid velocities under normal gravity and microgravity conditions. They found that the CHF in microgravity dramatically declines at low inlet liquid velocities compared with that in normal gravity. The effect of gravity on CHF is weaker as the inlet velocity increases. When the inlet liquid velocity exceeds 1.5 m/s, the influence of gravity almost vanishes and flow boiling is inertial-force-dominant. Konishi et al. [35,36] conducted the flow boiling experiments in a rectangular channel fitted with two opposite heating walls at the liquid inlet velocities of 0.1–1.9 m/s, and found that the enhancement in flow boiling heat transfer increases with increasing gravity level, whereas reduces with increasing microgravity level. This observation is similar to the results of others aforementioned. They also discovered that double-sided heating can achieve better heat transfer performance compared with that of single-sided heating at the same inlet velocities and heat fluxes. Konishi and Mudawar [37] summarized the research results regarding flow boiling and CHF in microgravity, and noted that the work of experimental investigation, correlations, mechanistic and computational models are still lacking for the application of flow boiling in future space systems.

From the previous literature review, it can be found that the research data of flow boiling heat transfer performance, especially for CHF in microgravity, is extremely lacking. As we know, the CHF of flow boiling is affected by many factors, such as inlet velocity and channel geometry parameter [38]. In addition, the experimental results of pool boiling on a smooth silicon chip and a micro-pin-finned chip in microgravity conducted by Xue et al. [39,40] and Zhang et al. [41] indicated that the CHF can be improved significantly due to the existence of micro-pin-finned structures. Therefore, surface modification is also an important factor influencing the CHF in microgravity. Based on the cooling requirement of electronic device in the future space equipment, the purposes of this paper are listed as follows: