Analysis of the critical heat flux of subcooled flow boiling in microgravity

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ABSTRACT

There is a significant decrease in flow boiling CHF when the inertial force of the fluid is not large enough in microgravity, but this tendency decreases with the increase of the inertial force. In the present study, the critical heat flux (CHF) of subcooled flow boiling at different gravity levels on smooth silicon surfaces was investigated. The working fluid is FC-72, with the subcooling of 15 K. The flow boiling heat transfer characteristics, including the CHF, wall temperatures and bubble behavior were studied. The effects of the heater length, channel height and flow velocity on the CHF were studied. It was found that the CHF increases with the increase of the channel height and flow velocity, but decreases with the increase of the heater length. A similar tendency was found for the ratio of the CHF in microgravity to that in normal gravity ($q_{CHF-\mu g}/q_{CHF-1g}$). The relation of the flow velocity, heater length, channel geometrical parameters, and $q_{CHF-\mu g}/q_{CHF-1g}$ was studied by the dimensionless analysis. Finally, a correlation for the prediction of $q_{CHF-\mu g}/q_{CHF-1g}$ was developed based on the dimensionless analysis and the prediction results agree quite well with the experimental data within $\pm 10\%$.

1. Introduction

Flow boiling is widely used in thermal management systems [1], energy power system [2], and microelectronic device heat dissipation [3]. It is well known that the flow boiling heat transfer performance in microgravity is different from that in earth gravity due to the absence of buoyancy [4]. The absence of the gravity severely weakens the buoyancy that helps the bubbles departure, causes more serious lateral bubble coalescence as well as premature heat transfer deterioration, and resulting in a decrease in CHF [5–9]. Therefore, it is of great significance to investigate the flow boiling heat transfer in microgravity for the thermal management and microelectronic device heat dissipation for space equipment. However, only a few experiments on flow boiling in microgravity have been reported [5–9] due to the difficulty in obtaining microgravity conditions and the complexity of the flow boiling experimental system.

Flow boiling in microgravity has been studied for more than 40 years. The main attention of the investigation on flow boiling in microgravity has been paid on the flow boiling heat transfer coefficient [10–13], bubble dynamics [14–16], the flow pattern of vapour/

gas–liquid flow [17–22], and critical heat flux [17,23–29]. CHF is a crucial parameter in flow boiling which determines the limit of nucleate boiling. Therefore, it is very important for the safety of the thermal management system and electronic devices.

Ohta [17] first measured the flow boiling CHF at high inlet quality in microgravity, but he only obtained one CHF point in microgravity ($q_{CHF,\mu g} = 3\text{--}4 \text{ W/cm}^2$ using R113 as working fluid) and he did not report the CHF value in normal gravity. Therefore, the effects of gravity on CHF is not clear. Using 2.1 s drop tower, Ma and Chung [23] measured the subcooled flow boiling CHF in microgravity around a platinum wire, they found that the CHF in microgravity tends to decline significantly compared to that in normal gravity under corresponding conditions. However, the gap between the CHF in microgravity and that in normal gravity was narrowed with the increase of flow velocity.

The longer the duration of microgravity, the more beneficial it is to obtain more accurate experimental data. Using parabolic flights, Zhang et al [24] and Konishi et al. [25,26] found that the vapor patches grew in length and formed a wavy vapor layer that propagated along the wall, permitting liquid access only in the wave troughs as CHF was approached, and the CHF was triggered by separation of the

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Nomenclature

Ch	channel number
CHF	critical heat flux (W/cm^2)
D_h	hydraulic diameter (mm)
Eo	Eötvös number
g	gravitational acceleration (m/s^2)
$1g$	earth gravity level (m/s^2)
H	channel height (mm)
I	heating current (A)
K	$CHF_{\mu g} / CHF_{1g}$ of pool boiling
L	heater length (mm)
L_c	capillary length (mm)
p_h	heated perimeter (mm)
p_w	wetted perimeter (mm)
q	heat flux (W/cm^2)
q_{con}	conductive heat flux (W/cm^2)
Sf	surface number
t	time (s)

T_1, T_2, T_3, T_4	wall temperatures ($^{\circ}C$)
T_a	average wall temperature ($^{\circ}C$)
T_f	liquid temperature ($^{\circ}C$)
T_{sat}	saturation temperature ($^{\circ}C$)
U	heating voltage (V)
V	inlet liquid velocities (m/s)
W	width of heater (mm)
We	Weber number

Greek symbol

ρ_g	vapor density (kg/m^3)
ρ_l	liquid density (kg/m^3)
σ	surface tension (N/m)
μg	gravitational acceleration in microgravity (m/s^2)
Δq_v	uncertainty of heat flux due to fluctuation of volume flow rate (W/cm^2)
ΔT_{sat}	wall superheat = $T_w - T_{sat}$ (K)
ΔT_{sub}	fluid subcooling = $T_{sat} - T_b$ (K)

liquid–vapor interface from the wall due to intense vapor effusion in the troughs. In addition, Zhang et al. [24] tested the flow boiling CHF in a single-heated rectangular channel with different inlet liquid velocities under different gravity conditions. They found that the $q_{CHF-\mu g}/q_{CHF-1g}$ increases with the increase of inlet velocity, and the effects of gravity levels can be neglected ($q_{CHF-\mu g}/q_{CHF-1g} > 0.9$) when the inlet velocity is greater than the threshold value (1.5 m/s). While Konishi et al. [25,26] found that the flow boiling heat transfer performance in a two opposite heated rectangular channel is better than that in a single-sided heated rectangular channel at the same conditions due to the faster fluid motion. For the flow boiling in a two opposite heated rectangular channel, the $q_{CHF-\mu g}/q_{CHF-1g}$ is larger than that in a single-sided heated rectangular channel at the same inlet velocity. Zhang et al. [27,28] tested the subcooled flow boiling CHF of smooth surface and micro-pin-finned surface in a single-side heated rectangular channel in microgravity via 3.5 s drop tower, and they found that except for the flow velocity, the geometric parameters of the channel, length of the heater and surface modification also show significant influence on $q_{CHF-\mu g}/q_{CHF-1g}$. Liu et al. [29] proposed a criterion for approximating the flow boiling CHF in microgravity by ground tests and proved it by drop tower experiments and a modified heat flux partitioning model. It was suggested that the CHF in microgravity can be obtained conveniently by the ground tests according to this criterion.

As mentioned above, it is difficult to measure CHF in microgravity flow boiling. Therefore, it will be very convenient if we can obtain the flow boiling CHF in microgravity through the empirical correlations, prediction models or ground tests. $q_{CHF-\mu g}/q_{CHF-1g}$ is a very important parameter for flow boiling heat transfer in microgravity. If the factors that affect $q_{CHF-\mu g}/q_{CHF-1g}$ and the corresponding influencing laws can be obtained, the CHF in microgravity can be easily obtained by the ground tests obtained under the corresponding working conditions. Zhang et al. [28] developed an empirical correlation for $q_{CHF-\mu g}/q_{CHF-1g}$ prediction. But due to the lack of experimental data, the database of Zhang et al. [28] is very limited and some factors that affect $q_{CHF-\mu g}/q_{CHF-1g}$ did not be analyzed comprehensively.

In summary, there are three shortcomings in the CHF of flow boiling in microgravity in literature: 1) only a few experimental data of flow boiling CHF in microgravity has been reported; 2) the research on the effects of the experimental conditions on flow boiling CHF in microgravity is still very scarce; and 3) no widely accepted empirical correlation for $q_{CHF-\mu g}/q_{CHF-1g}$ prediction has been proposed. Therefore, obtaining more basic experimental data, in-depth research on the influence of CHF and developing a widely accepted empirical correlation are very important for flow boiling research in microgravity.

In the present study, the subcooled flow boiling CHF was analyzed based on the drop tower experimental results in our previous study [29]. A comprehensive investigation on the effects of the flow velocity, heater length and channel size on $q_{CHF-\mu g}/q_{CHF-1g}$ based on the experimental results reported in our previous study and other literature was conducted. Furthermore, a correlation for the prediction of $q_{CHF-\mu g}/q_{CHF-1g}$ was developed based on the dimensionless analysis.

2. Experimental method

A method for approximating the CHF of subcooled flow boiling in microgravity by ground tests was proposed in our previous study. The method suggests that the flow boiling CHF in microgravity can be approximated by using the range of the CHF under the heater inclination of 315° and the CHF under the heater inclination of 135° in normal gravity under the corresponding conditions [29]. Based on this approximate method, five cases of drop tower tests were conducted. Firstly, considering the effects of the heater length, flow velocity and channel size, the experimental conditions for these five cases were determined. Next, the CHF under the heater inclination of 315° and 135° were measured on the ground. Then, the experimental matrix for drop tower tests was established based on the results of the ground tests. Finally, the drop tower tests were conducted based on the experimental matrix.

The subcooled flow boiling experiments in microgravity were conducted by the drop tower in NML of CAS, Beijing [30]. The tall of the drop tower is 116 m with about 61 m free fall height. The gravity level in microgravity (μg) is approximately $10^{-2}g$, where g is gravitational acceleration on the ground. The duration of the microgravity environment in each drop tower test is 3.5 s.

The experimental setup is schematically shown in Fig. 1. A micro vortex pump was used to pump liquid to the pipeline. The flow velocities (V), which were adjusted by a potentiometer and a valve, were 0.5 and 1.0 m/s for the drop tower tests. The flow direction is horizontal and the outlet pressure is 1 atm. The pressure drop between the inlet and outlet of the test section has been measured by a differential pressure transmitter in our previous study. It was found that the maximum pressure difference between the inlet and outlet is less than 1.4 kPa both under normal gravity and microgravity [28]. Therefore, the pressure drop between the inlet and outlet was neglected and test pressure can be approximated to 1 atm in the present study. To investigate the effects of the channel geometrical parameters on the CHF, two rectangular channels with a cross-section of $12 \times 3 \text{ mm}^2$ and $12 \times 5 \text{ mm}^2$ (width $\times$ height) were used. The heating surface was

1. Pump 2. Potentiometer 3. Turbine flowmeter 4. Valve 5. Pipeline 6. Test section 7. Tank 8. Rubber bag 9. Auxiliary heater 10. Condenser 11. Temperature controller 12. DC power 13. Thermocouples 14. Heated surface 15. Hall sensor 16. Data acquisition 17. Standard resistance 18. Light source 19. High speed camera

Fig. 1. Schematic diagram of the experimental setup.

horizontal upward placed in the channel and the camera was facing the heating surface. An auxiliary heater was installed in the tank for pre-heating the liquid to 41 °C. A rubber bag was used to maintain the pressure at 1 atm. The silicon surface was packaged in the plexiglass base by the heat insulation glue and then inserted into the rectangular channel, as shown in Fig. 2.

The smooth silicon surface was Joule heated by a DC power source. To achieve Joule heating, the N-doped silicon chips with a thickness of

0.5 mm and a width of 10 mm were used as the heating surfaces. Two copper wires were bond on the two opposite sides of the silicon surface by ultrasonic welding, and the contact resistance between the silicon surface and copper wires can be neglected, as shown in Fig. 2(a). To decrease the heat loss, the gap between the heater and the plexiglass base was filled with thermal insulation glue, as shown in Fig. 2(b). As better detailed in the following, the heat transfer can be considered only taking place effectively on the top side of the heater. To study the influence of the heater length on the CHF at different gravity levels, three types of heaters with the lengths of 10, 20 and 40 mm were used in the present study. The thermocouples were pasted on the bottom side of the heating surface with thermal conductive adhesive with an interval distance of 10 mm, as shown in Fig. 2(c).

The working fluid is FC-72, with the subcooling (ΔT_{sub}) of 15 ± 0.5 K. The working fluid was not degassed because the non-condensable gas only has a significant influence on boiling performance at the beginning of nucleate boiling, while for the CHF that the present study focuses on, the effects of non-condensable gas can be negligible [31–32]. Before the free fall process, the auxiliary heater was turned on through the remote control system to heat the fluid temperature to 41 °C. And then the fluid temperature was kept at 41 ± 0.5 °C by a PID temperature control system. To achieve the stable flow boiling state, the surface was heated for at least 2.5 mins before the drop capsule releases until the wall temperature change within 30 s is less than 0.2 K. A constant voltage was applied to the heating surface during the experiment. When CHF occurs, the wall temperature increases sharply, and the resistivity of the silicon chip increases with the increasing wall temperature, which leads to a decrease in the heating current and heat flux. In addition, these changes mentioned above is irreversible during the free-falling and the rising rate of the wall temperature is higher than

Fig. 2. Schematic diagram of the test section: (a) test chip soldering, (b) chip heating module, and (c) chip unit.

10 K/s. Therefore, the CHF can be classified by the tendency of wall temperature, heating current and boiling phenomenon. A high-speed camera that was fixed on the top of the heating surface at 1000 fps with a resolution of 256×1280 was used to recording the bubble behavior during the drop tower test.

Considering the influence of the heater length, flow velocity and channel height on the subcooled flow boiling CHF, five cases of drop tower experiments named L40V05H3, L20V05H3, L10V05H3, L40V10H3, and L40V05H5, respectively, were conducted. Only the region approximating the CHF in microgravity was investigated. Before the drop tower test, the flow boiling curves and the CHF were tested on the ground. Then, the heat flux (q) for each drop tower test was decided according to the criterion for approximating flow boiling heat transfer by ground tests [29]. The CHF in microgravity is smaller than that in normal gravity due to the lack of gravity. Therefore, the set value of heat flux for the drop tower test is smaller than that in normal gravity. For each case, two drop tower tests with different heat fluxes were conducted to obtain the region that contains the CHF value in microgravity. The experimental conditions were listed in Table 1. Due to the limit of the experimental resource, only 9 times of drop tower tests were conducted in the present study, and each test was only conducted once.

The fluid temperature was measured by a platinum resistance thermometer with the uncertainty of 0.23 K. T-type thermocouples (OMEGA TT-T36-SLE) with a diameter of 0.127 mm were used to measure the wall temperatures. The uncertainties of wall temperature are less than 0.36 K and 0.68 K in the steady-state and unsteady state, respectively. The signals of the wall temperatures (T_1, T_2, T_3, T_4), flow velocity (V), gravity acceleration (g), heating voltage (U) and the heating current (I) recorded by the data acquisition. The heat flux of the boiling surface (based on the measured heat flux minus the heat loss, ϵ) can be calculated as [33]

$$q = \frac{U \cdot I (1 - \epsilon)}{L \cdot W} \quad (1)$$

where L , W and ϵ represent the length, width of the heater, and the ratio of heat losses, respectively. The thickness of the thermal insulation glue with a heat conductivity coefficient of 0.2 W/m K in the gap between the heater and the plexiglass base is 2.5 mm. According to the one-dimensional Fourier law, the heat loss through the substrate of the heating surface is estimated to be less than 1.7% (L40V05H3 at $q = 19.3 \text{ W/cm}^2$).

The uncertainty of the measured heat flux can be calculated as

$$\frac{\Delta q}{q} = \sqrt{\left(\frac{\Delta U}{U}\right)^2 + \left(\frac{\Delta I}{I}\right)^2 + \left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta W}{W}\right)^2} \quad (2)$$

In the present study, only the data approaching the CHF were recorded (the minimum heat flux is 18.2 W/cm^2). The measurement uncertainties for $\Delta U/U$, $\Delta I/I$, $\Delta L/L$, and $\Delta W/W$ are 0.1%, 0.014%, 0.5% and 0.5%, respectively. Thereby the uncertainty of the measured heat flux is 0.7%. The heat conduction loss through the substrate of the heating surface ($\Delta q_{\text{con}}/q$) and the effects of the fluctuation of flow velocity on the heat flux ($\Delta q_v/q$) should also be considered in the present study. The maximum uncertainty of the heat flux caused by the fluctuation of the volume flow rate $\Delta q_v/q$ is approximately 1.1%. Therefore, the uncertainty of total heat flux is approximately 1.3%. More details on the experimental method can be found in our previous article [27–29].

3. Results

The flow boiling heat transfer performance with the condition of $L = 40 \text{ mm}$, $V = 0.5 \text{ m/s}$ and $H = 3 \text{ mm}$ was been reported in our previous study [27]. However, the CHF of the smooth surface in microgravity under this condition ($18.2\text{--}21.3 \text{ W/cm}^2$) is not precise. To obtain a more precise CHF value for this condition, one drop tower test

with a heat flux (q) of 19.3 W/cm^2 was conducted in the present study. The validation of the experimental setup has been reported in our previous study by comparing the measured boiling curves with those reported in publications [27]. Therefore, we only compared our experiment results under the condition of $L = 40 \text{ mm}$, $V = 0.5 \text{ m/s}$, and $H = 3 \text{ mm}$ with our previous study, as illustrated in Fig. 3. It can be found that these two boiling curves are very close to each other. Therefore, the experimental results in this study are reliable, and the results in Ref. [27] under this condition can also be used in the present study.

3.1. Effects of the heater length, flow velocity and channel height on the flow boiling CHF

The comparison of the wall temperatures, heating voltage, heating current, and flow velocity at different gravity levels for L40V05H3 is shown in Fig. 4, where $t > 0$ means the flow boiling in the stage of microgravity while $t < 0$ represents the flow boiling in the stage of normal gravity. Note that at the end of the free fall process, there is a deceleration device at the bottom of the tower to avoid the damage of the experimental device. During the deceleration process, the experimental device will continue to undergo large up and down vibrations, so the gravity acceleration curve shows an obvious oscillation process when $t > 3.5 \text{ s}$.

As shown in Fig. 4, the wall temperatures and heating current are found to remain steady under different gravity levels at $q = 18.2 \text{ W/cm}^2$ [27,29]. It is very important to ensure that the boiling can be reached to the stable-state within 3.5 s. Iceri et al. [33] carried out the flow boiling experiments in microgravity by parabolic flight. They found that the wall temperatures increase immediately after entering microgravity and then reach a stable state within 10 s. They also found that the increment in wall temperatures due to the decrease of gravity level decreases with the increase of mass velocity. However, the flow velocity (or mass velocity) in this study is much higher than that in Ref. [33] ($816 \text{ kg/m}^2\text{s}$ at $V = 0.5 \text{ m/s}$ and $1632 \text{ kg/m}^2\text{s}$ at $V = 1.0 \text{ m/s}$) and the stable flow boiling has been reached before entering the microgravity environment. Therefore, the increase of wall temperatures at the lower heat flux of each case is not significant after entering microgravity in the present study. The maximum temperature increase, which was observed from L20V05H3 at $q = 21.0 \text{ W/cm}^2$, is only 1.5°C after entering microgravity (Fig. A1 (a)). In this case, we also found that the wall temperatures increase immediately after entering microgravity, but they reach a stable state in a very short time (within 1 s). This phenomenon is similar to that reported in Ref. [33]. The evolution of wall temperature after entering microgravity was also verified through a simple simulation of transient thermal conductivity by commercial software Comsol 5.5 (please see Appendix B). Therefore, it can be considered that the boiling states for the lower heat flux of all the 5 cases have reached the steady-state during the drop tower experiments.

In addition, it can be found in Fig. 4 that the flow velocities are

Table 1
The experimental conditions and results on the ground.

Case number	L (mm)	V (m/s)	H (mm)	q (W/cm^2)	$q/q_{\text{CHF-1g}}$
L40V05H3	40	0.5	3	18.2 [27]	77.8%
	40	0.5	3	19.3	83.9%
L20V05H3	20	0.5	3	20.7	85.9%
	20	0.5	3	22.5	93.4%
L10V05H3	10	0.5	3	23.9	88.5%
	10	0.5	3	25.6	94.8%
L40V10H3	40	1.0	3	23.3	87.9%
	40	1.0	3	24.3	91.7%
L40V05H5	40	0.5	5	19.8	81.1%
	40	0.5	5	21.2	86.9%

Fig. 3. Comparison of boiling curves in the present study and previous study.

maintained stable whatever the flow boiling state and gravity level is. Therefore, the influence of flow boiling state and gravity level on flow velocity can be neglected in the present study.

For the higher heat flux of each case, for example, L40V05H3 at $q = 19.3 \text{ W/cm}^2$, the wall temperatures increase slowly at 0–0.5 s and then increases dramatically, accompanying the sharp decrease in heating current after $t = 0.5 \text{ s}$. This phenomenon indicates that the CHF reached under microgravity under this condition.

The comparison of bubble behavior at different gravity levels for this case is shown in Fig. 5. No remarkable distinction is observed in the bubble behavior between the microgravity condition and the normal condition at $q = 18.2 \text{ W/cm}^2$, except that the bubbles at the downstream of the heating surface in microgravity are slightly larger than that in normal gravity. While at $q = 19.3 \text{ W/cm}^2$, a very rapid transition from nucleate boiling to film boiling can be observed. Therefore, according to the comparison of Figs. 4 and 5, it can be inferred that the CHF does not occur at $q = 18.2 \text{ W/cm}^2$ in microgravity while the CHF has occurred at $q = 19.3 \text{ W/cm}^2$. Then, the CHF in microgravity for this case can be inferred to be between 18.2 W/cm^2 and 19.3 W/cm^2 . Similarly, the CHFs in microgravity for L20V05H3 and L10V05H3 can be inferred in the ranges of $20.7\text{--}22.5 \text{ W/cm}^2$ and $23.9\text{--}25.6 \text{ W/cm}^2$, respectively (See Appendix A).

The maximum ranges of uncertainty for the CHF for L40V05H3, L20V05H3, and L10V05H3 in microgravity are only 1.4, 1.9 and 1.8 W/

cm^2 , respectively, which are very close to each other. Bubbles are created on an artificial nucleation site between two-dimensional plates under terrestrial and microgravity conditions. It is well known that the bubbles tend to slide along the surface and coalesce to each other in microgravity compared to that in normal gravity due to the absence of gravity. Therefore, the bubble departure diameter is usually greater than that in normal gravity [15,16,20,21,24–26]. However, the influence of the gravity level on bubble behavior decreases with increasing flow velocity [15,16,20,21,24–26]. Ma and Chung [15] investigated the flow boiling heat transfer performance and boiling behavior of FC-72 with the subcooling of $26 \pm 2 \text{ K}$ and a flow velocity of $0.078\text{--}0.3 \text{ m/s}$. Serret et al. [16] studied the bubble behavior of HFE-7100 confined vapor bubbles with the subcooling of approximately 5 K and a flow velocity of $2\text{--}6 \text{ mm/s}$. Celata et al. [20] and Baltis et al. [21] tested the flow boiling performance and flow pattern in FC-72 at the inlet subcooling of $9\text{--}30 \text{ K}$ and flow velocity of $0.03\text{--}0.34 \text{ m/s}$. The flow velocity for L40V05H3, L20V05H3, and L10V05H3 is 0.5 m/s , which is much greater than that in Ref. [15,16,20,21]. Therefore, the bubble diameter in microgravity at $q = 18.2 \text{ W/cm}^2$, $q = 20.7 \text{ W/cm}^2$ in and $q = 23.9 \text{ W/cm}^2$ is observed only slightly larger than those in normal gravity (See Fig. 4, Fig. A2 and Fig. A4). Although these three cases have the same flow velocity and channel height, there is still a little difference in bubble behavior between each other: the distinction of bubble behavior between normal gravity and microgravity becomes more significant with the increase of heater length. It was reported that the bubble coalescence becomes more distinct in microgravity at the downstream of the heating surface, and the flow boiling state is very sensitive to the bubble coalescence when the heat flux approaching the CHF [28]. Therefore, the flow boiling state for L40V05H3 (the longest heater) is most sensitive to the bubble coalescence among these three cases, and it is much easier to trigger the dramatical deterioration of the flow boiling heat transfer, resulting in the lowest CHF among these three cases.

According to the method mentioned above, the CHFs for L40V10H3 ($L = 40 \text{ mm}$, $V = 1.0 \text{ m/s}$ and $H = 3 \text{ mm}$) and L40V05H5 ($L = 40 \text{ mm}$, $V = 0.5 \text{ m/s}$ and $H = 5 \text{ mm}$) were measured in the ranges of $23.3\text{--}24.3 \text{ W/cm}^2$ and $19.8\text{--}21.2 \text{ W/cm}^2$, respectively (Figs. A5–A8). The CHF for L40V10H3 is much greater than that for L40V05H3. Therefore, the effects of the increased flow velocity on the flow boiling CHF and the bubble behavior is similar to the effects of decreased heater length. The origin is that the increased flow velocity reduces the bubble departure diameter, and then weakens the bubble coalescence and increases the CHF (as shown in Fig. A6). A similar phenomenon can also be found in Ref. [24–26,28,29]. On the one hand, it was found that

Fig. 4. Comparison of the wall temperatures, heating voltage, heating current, and flow velocity in different gravity conditions for two levels of heat flux of L40V05H3.

Fig. 5. Comparison of bubble behavior in different gravity conditions for two levels of heat flux of L40V05H3. The gravity vector is into the page.

the accumulation of bubbles at the downstream of the heating surface is the main reason for heat transfer deterioration for the flow boiling with a small channel height and long heater [28,33,34]. Therefore, the higher channel is beneficial to achieve a higher CHF because it can reduce the accumulation of bubbles. On the other hand, the bubble tends to float up to the upper side of the channel in normal gravity, which causes the downstream of the heating surface to look blurry due to the overlap of the bubbles, as shown in Fig. A8. In addition, the downstream of the heating surface for L40V05H5 looks blurrier than that for L40V05H3, which means the increased of channel height is good for bubble lift-off and reduces the bubble coalescence on the heating surface. However, it is observed that the downstream of the heating surface looks clearer in microgravity compared to that in normal gravity, and the difference in bubble behavior between L40V05H5 and L40V05H3 is narrowed, as shown in Fig. 4 and Fig. A8. The reason is that the absence of gravity leads to the bubbles tending to slid on the surface instead of floating up to the upper side of the channel.

3.2. The comparison of the CHF in microgravity

The CHF for L40V05H3, L20V05H3, L10V05H3, L40V10H3, and L40V05H5 are in the ranges of 18.2–19.3 W/cm², 20.7–22.5 W/cm², 23.9–25.6 W/cm², 23.3–24.3 W/cm², and 19.8–21.2 W/cm², respectively. It was found that the CHF in microgravity increases with the increase of flow velocity and channel height, but decreases with the increase of heater length. A similar tendency in $q_{CHF-\mu g}/q_{CHF-1g}$ was observed. The $q_{CHF-\mu g}/q_{CHF-1g}$ for L40V05H3, L20V05H3, L10V05H3, L40V10H3, and L40V05H5 are in the ranges 77.8–83.8%, 86.1–93.9%, 88.3–95.0%, 88.1–92.2%, and 81.0–87.1%, respectively. Whereas, it is found that the increase of the $q_{CHF-\mu g}/q_{CHF-1g}$ for L40V05H5 is not as

large as that of L40V10H3 compared to L40V05H3. As mentioned above, the bubble lift-off diameter in normal gravity is smaller than that in microgravity. In addition, the capillary length ($L_c = [\sigma/g(\rho_l - \rho_g)]^{0.5}$) is approximately 0.76 mm in normal gravity, which is smaller than the height of the channel. Therefore, the higher channel is beneficial to ease the bubble accumulation at the downstream of the heating surface in normal gravity. However, the bubbles tend to slide on the surface, leading to more serious bubble coalescence on the heating surface [28], and the capillary length (7.6 mm) in microgravity gravity is larger than the channel height. Therefore, the effects of the channel height on the CHF in microgravity are not as large as that in normal gravity.

To find the critical velocity at which the effects of gravity can be negligible on the CHF of flow boiling ($q_{CHF-\mu g}/q_{CHF-1g} \geq 0.9$), Zhang et al. proposed a set of criteria by the dimensionless analysis [34]. They found if the effects of gravity on the flow boiling CHF can be ignored, three conditions must be met:

$$\frac{Bo}{We^2} = \frac{(\rho_l - \rho_g)(\rho_l + \rho_g)^2 \sigma g}{\rho_l^2 \rho_g^2 V^4} \leq 0.09 \quad (3a)$$

$$\frac{1}{Fr} = \frac{(\rho_l - \rho_g)gD_h}{\rho_l V^2} \leq 0.13 \quad (3b)$$

$$We_L = \frac{\rho_l \rho_g V^2 L}{(\rho_l + \rho_g) \sigma} \geq 2\pi \quad (3c)$$

where Bo is the Bond numbers ($Bo = g(\rho_l - \rho_g)D_h^2/\sigma$), We_L is the Weber numbers based on heated length and Fr is the Froude number. According to the criteria, the relationship between the critical velocity and the heater length can be obtained, as shown in Fig. 6. It can be found from Fig. 6 that the critical velocity mainly depends on the

Fig. 6. The relationship of the critical flow velocity with the heater length.

criteria of $Bo/We^2 \leq 0.09$ and $We \geq 2\pi$ in the present study, while the influence of the channel height can be negligible. In addition, the critical velocities for $L = 10, 20$ and 40 mm were calculated as $0.84, 0.71$ and 0.71 m/s, respectively. However, the experimental results indicated that the $q_{CHF-\mu g}/q_{CHF-1g}$ for L20V05H03 and L10H05H03 are larger than 0.9 when $V = 0.5$ m/s. Therefore, except for the flow velocity, the effects of the heater length should be carefully considered when investigating the influences of gravity on the CHF of flow boiling.

3.3. Dimensionless analysis of the $q_{CHF-\mu g}/q_{CHF-1g}$

Zhang et al. [28] analyzed effects of the heater length, channel geometrical parameter and surface modification on $q_{CHF-\mu g}/q_{CHF-1g}$, and developed an empirical correlation based on the dimensionless analysis, which can be expressed as

$$q_{CHF-\mu g}/q_{CHF-1g} = 0.179We^{0.325}Ch^{0.196}Sf^{2.568} + K \quad (4)$$

where Ch is the dimensionless channel number and Sf is the dimensionless surface number ($Sf = CHF_{ss,1g}/CHF_{m,1g}$, represents the ratio of the CHF on smooth surface to the CHF on modified surface in normal gravity), respectively; K is the $q_{CHF-\mu g}/q_{CHF-1g}$ in pool boiling ($V = 0$ m/s). Ch and K are given by

$$Ch = \frac{p_h}{p_w} \frac{1}{Eo} \frac{L}{L_c} = \frac{p_h L}{p_w h^2 \sqrt{g(\rho_l - \rho_g)/\sigma}} \quad (5)$$

$$K = 0.40Ch^{0.05}Sf^{-0.64} \quad (6)$$

where p_h/p_w is the ratio of heated perimeter to the wetted perimeter, Eo is the Eötvös number ($Eo = g(\rho_l - \rho_g)H^2/\sigma$), represents the degree of confinement of the channel height [4].

The comparison of the experimental results and predicted data by Eq. (4) is shown in Fig. 7. Note that the deviation of heat flux for each case in the present study is only 1.9 W/cm². Therefore, the average value of $q_{CHF-\mu g}/q_{CHF-1g}$ for each case was used in Fig. 7. It is found that remarkable deviations exist between the experimental results and predicted data for L40V05H3, L20V05H3, and L10V05H3. Although the development of Eq. (4) took the effects of the heater length, channel geometrical parameter and surface modification on $q_{CHF-\mu g}/q_{CHF-1g}$ into account, there are still some shortcomings for this correlation. Firstly, the development of Eq. (4) is based on the viewpoint of vapor accumulation in the channel. Therefore, the database in Ref. [28] is mainly

Fig. 7. Comparison of the experimental data and the predicted values of $q_{CHF-\mu g}/q_{CHF-1g}$ by the correlation in Ref. [28].

from the experimental results with the long heating surfaces of FC-72 (i.e. $L = 101.6$ mm in Ref. [24], $L = 114.6$ mm in Ref. [25]), and the threshold value for judging whether the vapor was accumulated or not in the channel was not given. For L20V05H3 and L10V05H3, the length of the heaters are only 10 mm and 20 mm, respectively, and the vapor accumulation cannot be observed in these two cases, as shown in Fig. A2 and Fig. A4. Therefore, this correlation is not suitable to predict the $q_{CHF-\mu g}/q_{CHF-1g}$ for these two cases. For L40V05H3, the increased channel height eased the bubble accumulation to some extent. Therefore, this correlation may be not suitable to predict the $q_{CHF-\mu g}/q_{CHF-1g}$ for this case. Secondly, the same weight was assigned to the three factors p_h/p_w , $1/Eo$ and L/L_c in Eq. (4), but the sensitivity of $q_{CHF-\mu g}/q_{CHF-1g}$ to these three factors are different. For instance, Kureta and Akimoto [35] found that the effects of the heated width on the CHF are small, but the CHF increases notably with the decrease of the heater length at the low inlet water temperature. Therefore, it is not accurate to assign the same weight to p_h/p_w , $1/Eo$, and L/L_c when developing the correlation for the $q_{CHF-\mu g}/q_{CHF-1g}$ prediction. Thirdly, the points of the database for the flow boiling CHF in microgravity are very limited, therefore, the scope of application is narrow, and the modification and improvement of the correlation are inevitable as the experimental data increase.

To improve the correlation, the factors that affect the $q_{CHF-\mu g}/q_{CHF-1g}$ should be considered carefully. In the present study, the effects of p_h/p_w , Eo , and L/L_c on $q_{CHF-\mu g}/q_{CHF-1g}$ were analyzed respectively instead of assigning the same weight to the three factors. Then, Eq. (4) can be rewritten as

$$q_{CHF-\mu g}/q_{CHF-1g} = aWe^b \left(\frac{p_h}{p_w} \right)^c Eo^d \left(\frac{L}{L_c} \right)^e Sf^f + K \quad (7)$$

$$K = 0.40Ch^{0.05}Sf^{-0.64}$$

where $Sf = 1$ in the present study because only the CHF results on the smooth surface were measured in the present study and most of the data from literature are based on the smooth surface. Note that K is based on the data of pool boiling. Therefore, it is not necessary to revise the expression of K . Then, the correlation for the prediction of the flow boiling $q_{CHF-\mu g}/q_{CHF-1g}$ on the smooth surface can be expressed as

$$q_{CHF-\mu g}/q_{CHF-1g} = aWe^b \left(\frac{p_h}{p_w} \right)^c Eo^d \left(\frac{L}{L_c} \right)^e + 0.40Ch^{0.05} \quad (8)$$

Table 2

The $q_{CHF-\mu g}/q_{CHF-1g}$ results based on the ground tests using FC-72 as the working fluid.

L (mm)	V (m/s)	H (mm)	q_{CHF-0° (W/cm ²)	$q_{CHF-315^\circ}$ (W/cm ²)	$q_{CHF-135^\circ}$ (W/cm ²)	range of $q_{CHF-\mu g}/q_{CHF-1g}$	average value of $q_{CHF-\mu g}/q_{CHF-1g}$
40	0.75	3	25.3	20.3	22.8	80.0–89.8%	0.849
20	0.75	3	28.6	25.9	27.6	89.1–96.6%	0.937
10	0.75	3	31.0	28.8	30.4	92.9–97.8%	0.954
20	1.0	3	30.9	28.7	29.8	92.9–96.7%	0.948
10	1.0	3	35.8	34.3	35.3	95.8–98.6%	0.972
20	0.5	5	24.8	20.7	22.5	83.5–90.8%	0.871
10	0.5	5	28.8	24.9	26.8	86.5–93.1%	0.898
40	0.75	5	25.5	20.8	23.8	81.3–93.3%	0.873
20	0.75	5	26.0	22.4	25.2	86.2–96.9%	0.916
10	0.75	5	33.5	30.8	31.8	92.0–94.9%	0.934
40	1.0	5	26.4	23.7	25.5	89.5–96.7%	0.930
20	1.0	5	29.0	26.3	28.3	90.7–97.7%	0.942
10	1.0	5	36.9	35.3	35.8	95.7–97.0%	0.963

Fig. 8. Comparison of the experimental data and the predicted values of $q_{CHF-\mu g}/q_{CHF-1g}$ by the improved correlation.

As mentioned above, the points of the database used to fit Eq. (4) are too limited to ensure the high precision and large scope of application of the correlation. Therefore, the number of points in the database was increased in the present study. Firstly, the five points from drop tower experiments are used in the present study. Secondly, Ref. [29] has provided a criterion for approximating the flow boiling CHF in microgravity by ground tests, in which the CHF in microgravity can be approximated by the range of CHF under the inclinations of 315° and 135° in normal gravity. The scope of application for this criterion is $V = 0.5\text{--}1.0$ m/s, $L = 10\text{--}40$ mm, $H = 3\text{--}5$ mm with the subcooling of 15 K at 1 atm. Therefore, the CHF data based on the ground tests are also measured and carefully used in the present study according to the scope of application of the criterion. The results based on the ground tests are listed in Table 2. Then, the constants a , b , c , d , and e can be obtained by fitting the data in Ref. [24,25] and that in the present study, and the correlation can be expressed as follows:

$$q_{CHF-\mu g}/q_{CHF-1g} = 0.473We^{0.299}\left(\frac{p_h}{p_w}\right)^{0.155}Eo^{-0.04}\left(\frac{L}{L_c}\right)^{-0.153} + 0.40Ch^{0.05} \quad (9)$$

The experimental data covered for fitting the correlation in the present study are for subcooled flow boiling with the following range of parameters: inlet velocity $V = 0.2\text{--}1.9$ m/s; length of heater $L = 10\text{--}114.6$ mm; subcooling $\Delta T_{sub} = 3\text{--}15$ K; and channel of height $H = 3\text{--}5$ mm.

The experimental results and predicted data by improved correlation are compared in Fig. 8. It can be found that the calculated results are in good agreement with the experimental data with a deviation of $\pm 10\%$. Therefore, when predicting the $q_{CHF-\mu g}/q_{CHF-1g}$, it is more reasonable to consider the effects of p_h/p_w , Eo and L/L_c separately.

It is found from Eq. (9) We has the maximum exponent in Eq. (9), indicating that flow velocity shows the strongest effect on $q_{CHF-\mu g}/q_{CHF-1g}$ and $q_{CHF-\mu g}/q_{CHF-1g}$ can be increased significantly by increasing flow velocity. In addition, p_h/p_w and L/L_c also play important roles in $q_{CHF-\mu g}/q_{CHF-1g}$. A notable increase of $q_{CHF-\mu g}/q_{CHF-1g}$ can also be obtained by increasing p_h/p_w or/and decrease the heater length. While the exponent of $Eo = -0.04$, is much smaller than those of p_h/p_w , Eo and L/L_c . Therefore, $q_{CHF-\mu g}/q_{CHF-1g}$ is not sensitive to the channel height when the channel height is in the range of 3–5 mm. Baldassari and Marengo [4] pointed out that the Eötvös number plays an important role in flow boiling heat transfer when the gravity tends to zero or when the tube diameter tends to zero. However, the range of the channel height in the present study is very narrow ($H = 3\text{--}5$ mm, and the corresponding range of Eo is 0.157–0.437). Therefore, the effects of the channel height (or Eo) on $q_{CHF-\mu g}/q_{CHF-1g}$ should be investigated further in future studies.

4. Conclusions

In the present study, the CHF of subcooled flow boiling in a single-side heated rectangular channel at different gravity levels on smooth silicon surfaces was investigated by drop tower experiments. The heat transfer performance, including the CHF, wall temperatures and bubble behavior were measured. The main findings from the study are concluded as follows:

- (1) The CHF increases with the increase of the channel height and flow velocity, but decreases with the increase of the heater length. A similar tendency was found for $q_{CHF-\mu g}/q_{CHF-1g}$.
- (2) The distinction of bubble behavior between normal gravity and microgravity becomes more sensitive to the increase of the heater length.
- (3) With the increase of the heater length or the decrease of the flow velocity and channel height, the flow boiling state is more sensitive to the bubble coalescence, which makes it easier to transit from the nucleate boiling to film boiling.
- (4) The dimensionless analysis for the influences of We , p_h/p_w , Eo and L/L_c was conducted based on the data of this study and the literature. We , p_h/p_w and L/L_c show the notable effects on $q_{CHF-\mu g}/q_{CHF-1g}$, while $q_{CHF-\mu g}/q_{CHF-1g}$ is not sensitive to Eo . $q_{CHF-\mu g}/q_{CHF-1g}$ can be increased significantly by increasing We , p_h/p_w or/and decrease the heater length. An improved correlation for the prediction of $q_{CHF-\mu g}/q_{CHF-1g}$ was developed based on the dimensionless analysis and it shows good agreements with the experimental data.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. . The flow boiling performance and bubble behavior of L20V05H3, L10V05H3, L40V10H3 and L40V05H5

The comparison of the wall temperatures, heating voltage, heating current, and flow velocity in different gravity conditions for L20V05H3 is shown in Fig. A1Fig. A3 and the comparison of bubble behavior at different gravity levels for this case are shown in Fig. A2. As shown in Fig. A1, the wall temperatures increase slightly in microgravity conditions at $q = 20.7 \text{ W/cm}^2$. However, the stable nucleate flow boiling is still maintained at this heat flux, and almost no difference in bubble behavior can be observed, as shown in Fig. A2. When the heat flux is increased to 22.5 W/cm^2 , the wall temperatures increase dramatically at $t = 0.8 \text{ s}$, and the nucleate flow boiling transit to the film boiling within 2 s. Therefore, the CHF in microgravity can be inferred in the range of $20.7\text{--}22.5 \text{ W/cm}^2$ for this case.

The comparison of the wall temperatures, heating voltage, heating current, and flow velocity in different gravity conditions for L10V05H3 is shown in . The wall temperature remains stable at $q = 23.9 \text{ W/cm}^2$, while it increases dramatically at 0.4 s at $q = 25.6 \text{ W/cm}^2$. Similar to the L40V05H3 and L20V05H3, the CHF in microgravity for L10V05H3 can be inferred in the range of $23.9\text{--}25.6 \text{ W/cm}^2$. The bubble behavior at $q = 23.9 \text{ W/cm}^2$ is similar to that for L40V05H3 and L20V05H3, As shown in Fig. A4. However, it transits to film boiling within 1 s, which is much faster than that of L40V05H3 and L20V05H3. The CHF in microgravity increases with the decrease of the heater length, while the time from nucleate boiling to film boiling decreases as the length of the heater decreases.

Fig. A1. The wall temperatures, heating voltage, heating current, and flow velocity in different gravity conditions for two levels of heat flux of L20V05H3 [29].

Fig. A2. Comparison of bubble behavior in different gravity conditions for two levels of heat flux of L20V05H3 [29]. The gravity vector is into the page.

Fig. A3. The wall temperatures, heating voltage, heating current, and flow velocity in different gravity conditions for two levels of heat flux of L10V05H3.

Fig. A4. Comparison of bubble behavior in different gravity conditions for two levels of heat flux of L10V05H3. The gravity vector is into the page.

Fig. A5. The wall temperatures, heating voltage, heating current, and flow velocity in different gravity conditions for two levels of heat flux of L40V10H3.

Fig. A6. Comparison of bubble behavior in different gravity conditions for two levels of heat flux of L40V10H3. The gravity vector is into the page.

Fig. A7. The wall temperatures, heating voltage, heating current, and flow velocity in different gravity conditions for two levels of heat flux of L40V05H5.

Using the same method shown above, the CHF for L40V10H3 and L40V05H5 can be obtained in the ranges of 23.3–24.3 W/cm^2 and 19.8–21.2 W/cm^2 , respectively (as shown in Fig. A5 and Fig. A7). It can be observed that the flow boiling maintained stable from 0 s to 2.7 s, as shown in Fig. A6, and the transition of the flow boiling is much slower than that for L40V10H3, suggesting that the increasing flow velocity slows down the transition process of flow boiling. As for L40V05H5, the bubble coalescence becomes much seriously in microgravity although the wall temperatures remain steady at 19.8 W/cm^2 (see Fig. A8). The flow boiling completely converts to film boiling within 3 s, which is similar to that for L40V05H3. In addition, the CHF for L40V05H5 is only slightly increased compared to that for L40V05H3, which indicates the effects of the increased channel height on the CHF is not as large as that of the increased flow velocity.

Fig. A8. Comparison of bubble behavior in different gravity conditions for two levels of heat flux of L40V05H5. The gravity vector is into the page.

Appendix B. . Wall temperature evolution during the drop tower experiments.

To ensure that the duration of the drop tower experiment (3.5 s) is sufficient for the present study, it is very important to verify the evolution of wall temperature during the drop tower experiment. Before entering the microgravity environment, the stable boiling heat transfer state has been reached. After entering the microgravity, there is a certain increase in the wall temperature, which causes a decrease in the heat transfer coefficient. To verify the wall temperature during the drop tower experiments, A simple transient thermal conductivity simulation was carried out by commercial software (Comsol 5.5). In the present study, the maximum temperature increase (approximate 1.5 °C) after entering microgravity can be observed from L20V05H3 at $q = 20.7 \text{ W/cm}^2$, which means that the change of gravity level under this condition will cause the most obvious disturbance to heat transfer. Therefore, this case was used for simulation. It should be noted that all the cases which have reached the CHF are not taken into consideration because they have reached CHF and are still in an unstable state at $t = 3.5 \text{ s}$. To approximate the boiling heat transfer, the boiling heat transfer coefficient was applied onto the silicon surface. The silicon surface was treated as a body heat source with a heat flux of $4.2 \times 10^8 \text{ W/m}^3$. The model and boundary conditions are shown in Fig. B1.

Fig. B1. The 3-D model and boundary conditions for the transient thermal conductivity simulation of L20V05H3 at $q = 20.7 \text{ W/cm}^2$.

Fig. B2. The evolution of the wall temperature during the transient simulation.

Before the transient thermal conductivity simulation, a stationary thermal conductivity simulation based on the normal gravity conditions was carried out by applying the heat transfer coefficient of 5385 W/(m²·K). Then, the transient simulation was carried out based on the results of the stationary thermal conductivity simulation. A heat transfer coefficient of 5185 W/(m²·K) was applied on the heating surface. The transient time was set as 30 s with a step of 0.5 s.

The evolution of wall average temperature is shown in Fig. B2. It can be seen from the figure below that the wall temperature increases very significantly after entering microgravity. With the increase of time, the rate of wall temperature increase decreases rapidly. The average wall temperatures are increased to 80.33 °C at $t = 3.5$ s, which are very close to the wall temperature at $t = 30$ s (80.35 °C). Therefore, it can be considered that the boiling states for the lower heat flux of all the 5 cases have reached the steady-state during the drop tower experiments.

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