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Research Paper

A modified bubble dynamics model for predicting bubble departure diameter on micro-pin-finned surfaces under microgravity

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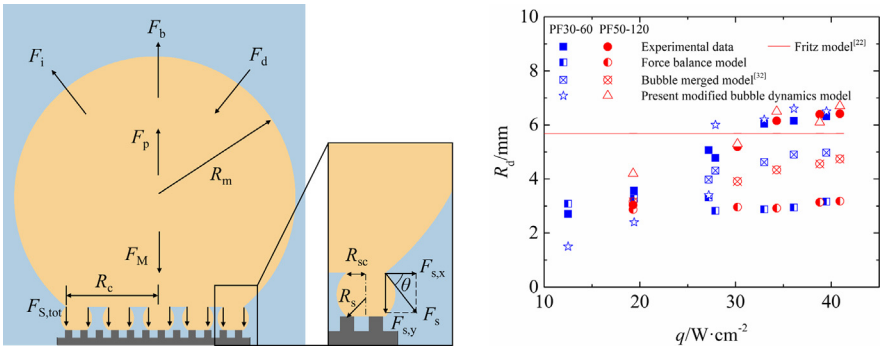
HIGHLIGHTS

- Small bubbles under the primary bubble prevents the primary bubble from departing.
- Drag force of small bubbles on primary bubble was considered as surface tension.
- Surface tension force plays an important role on the primary bubble dynamics.
- The modified bubble dynamics model predicts the bubble departure diameter well.

GRAPHICAL ABSTRACT



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ABSTRACT

The micro-pin-finned structure can effectively enhance the boiling heat transfer both in terrestrial gravity on earth and microgravity environments in space, while the mechanism of boiling heat transfer is very complex. By the observation of the bubble behaviors such as growth, coalescence and departure, the dynamic process is analyzed. For the smooth surface, the traditional bubble dynamics model could accurately predict the bubble departure diameter; while for the micro-pin-finned structure surface under microgravity environment, there was a relatively large deviation for this model. The reason is that the traditional bubble dynamics model for the smooth surface was originally established with the perspective of force balance analysis of single bubble, which did not consider the strong interaction among the bubbles on the micro-pin-finned surfaces. According to the experimental phenomena under microgravity environment, there are several small bubbles sitting under a primary bubble on the micro-pin-finned surface. The interaction between the small bubbles and the primary bubble prevents the departure of the primary bubble. A modified bubble dynamics model based on force balance is proposed to predict bubble departure diameter well on the micro-pin-finned surface, which considers the role of drag force of small bubbles beneath the primary bubble.

1. Introduction

As an efficient heat exchange method, boiling heat transfer has been widely applied for cooling in numerous fields, such as power generation, electronic device cooling and chemical production on earth and active thermal management system, power cycle,

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Nomenclature

A	heat surface area, m^2
C_d	drag force coefficient
c_p	specific heat capacity, J kg^{-1} K^{-1}
D	bubble diameter, mm
F_b	buoyancy force, N
F_d	drag force, N
F_i	inertial force, N
F_M	Marangoni force, N
F_p	pressure difference force, N
F_S	surface tension force, N
Fo	Fourier number
f_d	departure frequency, s^{-1}
g	gravitational acceleration at the microgravity condition, m s^{-2}
g_0	gravitational acceleration at the terrestrial condition, m s^{-2}
h_{fg}	liquid's latent heat of vaporization, J kg^{-1}
Ja	Jacob number
L	side length of heater surface, cm
m	mass of vapor, kg
n	the quantity of small bubbles
ΔP	pressure drop, Pa
Pr	Prandtl number
q	heat flux, W cm^{-2}
Δq_{tot}	overall uncertainty of heat flux, W·cm^{-2}
Δq_{con}	uncertainty of heat flux due to heat loss through substrate conduction, W·cm^{-2}
Δq_{tra}	uncertainty of heat flux due to heat loss through transient effect, W·cm^{-2}
R	bubble radius, mm
R_x, R_y	bubble radius in horizontal and vertical directions, mm
Re	Reynolds number
T_{sat}	saturation temperature, °C
T_b	temperature of bulk temperature, °C
ΔT_{wb}	temperature difference between wall and bulk liquid $\Delta T_{wb} = T_w - T_b$, °C
t_c	growth cycle, s
u	velocity of the rising bubble, m s^{-1}
V	bubble volume, m^3
x_{left}, x_{right}	coordinate in horizontal direction for the detached bubble, mm
y_{up}, y_{down}	coordinate in vertical direction for the detached bubble, mm

Greek symbols

β	the ratio of bubble radius
ξ	constant
ν	kinematic viscosity, m^2 s^{-1}
ρ	density, kg m^{-3}
σ	surface tension, N m^{-1}
θ	contact angle, deg

Subscripts

ave	average
c	contact line
d	departure
l	liquid phase
m	primary bubble
s	small bubble
tot	total
v	vapor phase

storage and transfer of cryogenic fluids in space. The advantage of boiling heat transfer is that a great deal of heat can be taken away while maintaining a low superheat compared with natural/forced convection without phase change, which leads to a high heat transfer coefficient. However, the heat dissipation capacity is limited by the upper limit of cooling, i.e., the critical heat flux (CHF). Studies on CHF enhancement have generally considered porous coatings [1–3], structures of various sizes fabricated on the heated surface [4–6], nanofluids [7–14] and so on. Moreover, the requirements for distance, duration and power of the manned space missions in the future promote the development of highly integrated circuits. The resulting problem is the dramatic increase in heat flux of electronic devices. Besides, the absence of buoyancy in microgravity can significantly deteriorate the heat transfer performance. Therefore, the study of boiling heat transfer under microgravity is very important for the design of heat dissipation equipment.

Merte et al. [15,16] conducted long-duration microgravity pool boiling experiments with R-113 on board NASA's Space Shuttle. They postulated that the thermocapillary reaction force plays a significant role in bubble nucleation and growth in microgravity, and therefore influences heat transfer effectiveness. Xue et al. [17] conducted pooling boiling heat transfer research of FC-72 on micro-pin-finned surfaces under microgravity by using drop tower. The coalescence of bubbles was extremely tempestuous and the bubble departure diameters were much larger under microgravity, which showed that the micro-pin-finned structures could also improve the heat transfer performance under microgravity. As for flow boiling at microgravity, Misawa [18] investigated subcooled and saturated flow boiling of R-113 in both drop tower (1.25 s at 0.02 g_0) and NASA's Learjet experiments. Flow patterns were shown to transition earlier in microgravity, but differences in flow behavior diminished at high vapor quality. Luciani et al. [19,20] employed inverse methods to estimate the local heat transfer coefficient. They reported heat transfer enhancement in all microgravity conditions, with average heat transfer coefficients as much as 30% higher than terrestrial data. Ma and Chung [21] investigated subcooled flow boiling of FC-72 across a heated 0.254 mm platinum wire in a 2.1 s drop tower. They measured an appreciable shift in boiling curve to lower heat fluxes compared to terrestrial gravity, indicating significant reduction in heat transfer effectiveness.

Many researchers have studied the mechanism of boiling heat transfer for several decades of year and proposed many models such as transient conduction, microlayer evaporation, RPI wall boiling model, partitioning model and so on. Some key boiling parameters like bubble departure diameter, which have been studied by plentiful research at terrestrial gravity, should be carefully identified due to the significant impact on the boiling physics. The earliest study of bubble departure diameter was the correlation proposed by Fritz [22], which simplified the departure of bubble as the result of force balance between upward buoyancy and downward surface tension. After that, many researchers modified the Fritz correlation to fit their experimental results, respectively. Cole et al. [23,24] studied the bubble growth and departure at subatmospheric pressure. A bubble departure diameter correlation associated with Jacob number was proposed.

In order to predict the boiling heat transfer well and design a compact heat sink in space, it is of great significance to study the bubble dynamics such as departure diameter at microgravity,