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Experimental study on the stagnation line heat transfer characteristics with high-velocity free slot jet impingement boiling

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ABSTRACT

In this paper, the stagnation line heat transfer characteristics and critical heat flux (CHF) of small slot jet impingement boiling were experimentally investigated. Water with the Reynolds number range 34,013–136,054, the size of slot jet nozzle of 12 mm × 1 mm, and the non-dimensional nozzle to target spacing of 0.2 were used. Besides, heat transfer surface sizes were 5 mm × 1 mm and 1.5 mm × 1 mm. It was found that the stagnation line heat transfer characteristics of the jet impingement nucleate boiling in the fully developed region are irrelevant to jet velocity, subcooling and heater size for the slot jet impingement in the present experimental range. The heat transfer correlation of nickel foil heater for the jet impingement nucleate boiling in the fully developed region was obtained. Meanwhile, the CHF of the jet impingement boiling on the stagnation line was also studied. Using the experimental data to modify the semi-empirical and semi-theoretical correlation proposed previously for predicting the CHF, its modified form with heater size effect was also obtained. Through increasing jet velocity and subcooling while decreasing heater size, extremely critical heat fluxes ($>10^8$ W/m^2) were achieved in the experiment, and its maximum value was 1.14×10^8 W/m^2. In addition to decreasing heater size to a moderate value, it is also necessary to change heater's surface features including CA to achieve a higher heat flux.

1. Introduction

The increasing development of the existing chip, aviation and military technology has brought increasingly demanding cooling requirements. Temperature requirements need to be achieved under high heat flux operation. In response, jet impingement boiling, which is able to achieve higher heat transfer coefficient and CHF, has become one of the most promising cooling solutions. For the study of jet impingement boiling on the stagnation line (jet diameter ⩾ heater diameter), it was found that jet velocity, heater diameter, fluid properties and solid–liquid contact angle (CA) all have effect on the heat transfer characteristic and CHF [1–10]. What's more, systematic steady experimental study [11] was conducted to investigate the effect of CA on the stagnation line CHF of high-velocity circular jet impingement boiling. And the semi-theoretical and semi-empirical correlation for predicting CHF was proposed. Detailed exploration on its heat transfer characteristics under high jet velocity and wide CAs (including the hydrophilic and hydrophobic surface) was also provided. A further research [12] explored the technical means to achieve the theoretical ultimate CHF (2×10^8 W/m^2). The heater with direct resistance heating combined with high-velocity slot jet impingement cooling on the stagnation line is chosen to be the most promising approach to achieve such a high heat flux. The effects of jet velocity and subcooling on the CHF of the high-velocity slot jet impingement boiling were also obtained from both experimental study and theoretical analysis. Table 1 is the summary of literature of jet impinging.

Li et al. [12] investigated the critical heat flux of high-velocity slot jet impinging on the stagnation zone under saturated boiling and subcooled boiling experimentally. The working fluid is deionized water, and nozzle exit size 12 mm in length and 1 mm in width with the jet velocity of 4–43 m/s and subcooling of jet 5–99 K under atmosphere pressure. Their study shows that the effect of lower jet velocity is positive; but it gradually turns to be negative when the stagnation pressure of the increasing velocity approaches 1/3 of the critical pressure. Besides, subcooled jet impingement can break through the bubble layer on the heater surface resulting in better solid–liquid contact. The highly diffusive heat transfer caused by bubble growth and collapse under subcooled jet impingement will increase the CHF. Wolf et al. [12] studied local jet impingement boiling heat transfer for a rectangle nozzle of 10.2 × 102 mm and jet velocity of 2.0–5.0 m/s. At surface temperatures in excess of saturation, the onset of nucleate boiling

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Nomenclature

B	correlation factor, (–)
C	correlation factor, (–)
c_p	specific heat, (J/kg/K)
$C_{L'}$	heater length effect coefficient, (–)
d	width of jet nozzle/ heater, (m)
h	heat transfer coefficient, (W/m^2/K)
h_{lv}	latent heat of evaporation, (J/kg)
I	current through the heat transfer surface, (A)
L	length of nickel foil, (m)
L'	non-dimensional length, (–)
P	pressure, (Pa)
k	thermal conductivity, (W/m/K)
N_a	active nucleate site density, (–)
Nu	Nusselt number, (–)
Pr	Prandtl number, (–)
q_w	wall heat flux, (W/m^2)
q_c	critical heat flux (W/m^2)
R	electric resistance (Ω)
Re	Reynolds number (–)
T	temperature (K)
$\bar{T}$	average temperature of the heater (K)
ΔT_{sat}	wall superheat; $\Delta T_{sat} = T_w - T_0$ (K)
ΔT_{sub}	subcooling of water; $\Delta T_{sub} = T_0 - T_l$ (K)
U	voltage between the two cuboid copper electrodes (V)
V	jet velocity exited from nozzle (m/s)
z	non-dimensional nozzle to target spacing
h	heat transfer coefficient

Greek symbols

σ	surface tension (N/m)
ρ	density (kg/m)
θ	solid–liquid contact angle (°)
ξ_{loss}	ratio of the heat loss to the total heat (–)
Φ	heat source density (W/m^3)
α	temperature coefficient of resistance (K^{-1})
δ	thickness of the heater (m)

Subscripts

0	saturation state
b	nucleate boiling
l	liquid
w	wall
v	vapor

Abbreviations

CHF	critical heat flux
CA	solid–liquid contact angle
HTC	heat transfer characteristics
ONB	onset of nucleate boiling

was identified by a marked increase in the convection coefficient. The effect of jet velocity on the heat transfer was most pronounced in the single-phase and partial boiling regimes. At the lower velocity (2.0 m/s) the convection coefficient increased with increasing surface temperature throughout the partial boiling regime. However, for the higher velocity (5.0 m/s), an initial rise in the convection coefficient with increasing ΔT_{sat} was followed by a much larger range of wall superheats for which the convection coefficient was nearly constant. In the fully-developed boiling regime, convection was dominated by the intense, bubble-induced mixing and latent heat effects, and heat transfer was independent of the jet velocity.

Extensive researches have been conducted to evaluate the effect of heater size on pool boiling heat transfer characteristics. Baker [18] found that the heat transfer coefficient will slightly increase with decreasing heater size. However, Park and Bergles [19] observed that heater size does not affect heat transfer characteristics significantly. And Lienhard [20] verified the CHF will decrease to a certain value with increasing heater size by experiment and analysis. He also stated that the vapor column number present on the heater will decrease with decreasing heater size, and it will be more difficult for vapor to cover the heater. Thus, the CHF gets enhanced. Rainey and You [21] attribute the CHF enhancement mechanism to the rewetting resistance of fluid. For a small heater, unlike an infinite flat plate case, a majority of the rewetting fluid is supplied from the sides rather than from above. As the heat flux increases, the vapor dwelling time and amount covering the heater increase. This, in turn, increases the rewetting resistance to the cooler bulk liquid advancing over the heater. Thus, the rewetting resistance should be a function of flow path distance parallel to the heater. The larger heater offers a longer resistive distance to the hot spots at its center and this leads to a lower CHF.

For the above pool boiling researches, there is a consistent point that the heater size will not affect the pool boiling heat transfer characteristics, but only affect the CHF. As an extension research from pool boiling CHF mechanism, Liu and Zhu [10] used the concept of the maximum liquid macrolayer thickness to predict CHF. A semi-theoretical and semi-empirical correlation to predict the stagnation line CHF of steady boiling for the circular jet impingement was derived. And this correlation is based on the theoretical analysis of Helmholtz instability in gas–liquid interface theory, which is also similar in the pool boiling CHF mechanism. Thus, it could reasonably be inferred that heater size also has the similar effect on the stagnation line CHF of the jet impingement boiling just as in the pool boiling experiments. In response to this assumption, the present paper will investigate the effect of heater size on the stagnation line heat transfer characteristics and CHF of the small slot jet impingement boiling. Following the previous research [12], the heater with direct resistance heating combined with high-velocity water slot jet impingement cooling on the stagnation line is also chosen to be the present experimental approach. Changing heater length and keeping heater width unchanged makes the study of size effect on heat transfer characteristics feasible. Using the experimental data to modify the semi-empirical and semi-theoretical correlation proposed previously for predicting the CHF, its modified form with heater size effect is also obtained. Through increasing jet velocity and subcooling while decreasing heater size, extremely high heat fluxes (>10^8 W/m^2) are achieved in the experiment.

2. Experimental apparatus and procedure

Fig. 1 shows the schematic diagram of the experimental apparatus. It mainly consists of a test chamber, a water circulation system, as well as measurement and power supply systems. Deionized water with the electric conductivity of about 3 μΩ/cm was used as the working fluid. Deaeration was performed by boiling the water in a water tank at atmospheric pressure for 2 h. After deaeration, water was cooled or heated to a predetermined temperature at atmospheric pressure. After that, the water was drained from the tank by a multistage centrifugal pump and exited