International Journal of Heat and Mass Transfer 70 (2014) 1–9

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Experimental study on critical heat flux of steady boiling for high-velocity slot jet impinging on the stagnation zone

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ARTICLE INFO

Article history:
Received 21 December 2011
Received in revised form 9 September 2013
Accepted 24 October 2013
Available online 13 November 2013

Keywords:
Jet
Boiling
Critical heat flux
Impact velocity

ABSTRACT

In this paper, the critical heat flux (CHF) of high-velocity slot jet impinging on the stagnation zone under saturated boiling and subcooled boiling were investigated experimentally. Two non-dimensional semi-theoretical and semi-empirical correlations to predict the CHF under saturated and subcooled boiling conditions were proposed from experimental data respectively. The mechanism of the subcooling and impact velocity effect on the CHF of jet impinging under steady boiling conditions were quantitatively explained. The high impact velocity has been observed to affect the CHF by two means. On one hand, the jet flow breaks through the vapor layer and brings fresh fluid, which always plays a role in strengthening the CHF. On the other hand, the high-velocity causes an increase of wall stagnation pressure, which will increase the CHF initially. When the wall stagnation pressure approaches 1/3 of the critical value, the CHF turns to decrease gradually. According to this trend, there should exist an ultimate CHF of steady boiling for jet impinging on the stagnation zone. The concepts of ultimate impact velocity and corresponding ultimate CHF are also obtained from the theoretical analysis.

1. Introduction

With the rapid development of electronic technology, the high demanding for the compact cooling devices to deal with the increasing power dissipation has become an unprecedented challenge for heat transfer technology. With excellent heat transfer coefficient, liquid jet impinging has been widely applied for industrial cooling and electronic thermal management. It can be subdivided into five categories: free surface, plunging, submerged, confined and wall jets. The free surface jet is the most widely applied method, by means of injecting the liquid into an immiscible atmosphere and impinging on the surface directly. The two principal configurations for free surface jet are circular jet and slot jet. The slot jet, though being less researched than the circular jet, has more benefits, such as higher cooling effectiveness, greater uniformity and easier to control. Thus the slot jet has more potential to obtain higher heat flux and to further downsize the compact electronic devices. Subcooled high-velocity liquid jet can break through the bubble layer when impinging on the heat transfer surface, which will enhance solid–liquid contact and improve the critical heat flux (CHF) greatly. So, the liquid jet impinging with subcooled boiling is the most effective method to increase the maximum heat flux among all the steady-state heat transfer forms. From the perspective of two phase flow/ heat transfer, the basic technical indicator for equipment cooling capacity is the CHF value. Increasing the CHF has vital significance both in basic research and practical applications. It is reported that the value of CHF can reach 10^7 W/m^2 in water jet impinging steady boiling experiments, compared to 10^6 W/m^2 in water pool boiling.

However, the CHF cannot be increased infinitely. There exists a theoretical ultimate value, which is an order of magnitude higher than the reported experimental data. According to the thermodynamic theory model of Gambill and Lienhard [1], the ultimate CHF can be expressed as follows,

$$q_{c,\max} = \rho_v h_{lv} \sqrt{RT_0/(2\pi M)} \tag{1}$$

where, $q_{c,\max}$ is the ultimate CHF, ρ_v is the density of vapor, h_{lv} is the latent heat of evaporation, R is the gas constant number, M is the molecular weight and T_0 is the saturated temperature.

According to the correlation (1), the theoretical ultimate CHF is about 2.23×10^8 W/m^2 at the atmospheric pressure when water is taken as the working fluid (as far as we know, water is the working fluid with the maximum heat transfer coefficient). For the steady boiling of jet impingement, most previous studies focused on the free surface jet boiling heat transfer characteristics with heat transfer surface diameter bigger than the nozzle diameter [2–13]. The stagnation region coinciding with that of the impinging jet in both size and location will have the maximum heat transfer coefficient and the CHF. The heat transfer surface with a diameter smaller than or equal to the nozzle diameter is required to obtain the CHF of the stagnation region, in order to prevent the region

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.10.058

Nomenclature

c_0	correlation factor, (–)
c	specific heat, (J/kg/K)
d	width of jet nozzle and heater, (m)
k	thermal conductivity, (W/m/K)
G	mass flux of liquid jet, (kg/m^2/s)
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, (–)
M	molecular weight, (g/mol)
p	pressure, (Pa)
q	wall hat flux, (W/m^2)
q_c	critical heat flux, (W/m^2)
$q_{c,\max}$	ultimate critical heat flux, (W/m^2)
R	gas constant, (J/mol/K)
T	temperature, (K)
ΔT_{sub}	subcooling of cooling water; $\Delta T_{sub} = T_0 - T_l$, (K)
U	voltage between the two cuboid copper electrodes, (V)
V	impact velocity exited from nozzle, (m/s)
V_c	ultimate impact velocity

Greek symbols

σ	surface tension, (N/m)
ρ	density, (kg/m)
θ	solid–liquid contact angle, (°)
δ	thickness, (m)

Subscripts

0	saturation state
l	liquid
h	heat transfer surface
v	vapor
s	stagnation region
∞	environment atmospheric

outside the stagnation region from burning out in advance due to less heat transfer coefficient. So, the jet impinging on the stagnation zone in the present study is defined as the free surface jet with a nozzle having the same diameter as the heat transfer surface. However, the studies focusing on the steady boiling for free surface jet impinging on the stagnation zone are still insufficient [14–26]. Most of these studies are focusing on steady boiling for circular jet impinging on the stagnation zone. For example, Liu [26] used the concept of the maximum liquid macrolayer thickness for predicting CHF. A semi-theoretical and semi-empirical correlation to predict the CHF of steady boiling for circular jet impinging on the stagnation zone was derived. And this correlation is based on the theoretical analysis of Helmholtz instability in gas–liquid interface theory.

$$\frac{q_{c,0}}{Gh_{lv}} = c_0\left(1+\frac{\rho_v}{\rho_l}\right)^{1/3}\left(\frac{\sigma\rho_l}{G^2 d}\right)^{1/3}\left(\frac{\rho_v}{\rho_l}\right)^{1.4/3} \tag{2}$$

where, $q_{c,0}$ is the CHF of saturated liquid, G is the mass flux of liquid jet, ρ_l is the density of liquid, σ is surface tension, d is the diameter/width of jet nozzle and heater, c_0 is a correlation factor and could be determined from the experimental data.

For most working fluids, the first term on the right of this dimensionless equation can be neglected, so Eq. (2) can be written as;

$$\frac{q_{c,0}}{Gh_{lv}} = c_0\left(\frac{\sigma\rho_l}{G^2 d}\right)^{1/3}\left(\frac{\rho_v}{\rho_l}\right)^{1.4/3} \tag{3}$$

The correlation was obtained in the study of Qiu and Liu [21] for the CHF of low and moderate velocity ($V < 10$ m/s) saturated liquid steady boiling for circular jet impinging on the stagnation zone at the atmospheric pressure. For the saturated liquid steady boiling for jet impinging on heat transfer surface of copper cylinder, Eq. (4) can be obtained.

$$\frac{q_{c,0}}{Gh_{lv}} = 0.13\left(\frac{\sigma\rho_l}{G^2 d}\right)^{1/3}\left(\frac{\rho_v}{\rho_l}\right)^{1.4/3} \tag{4}$$

The liquid properties with low velocity jet can be used as constant at atmospheric pressure. As a result, Eq. (4) can be further simplified to Eq. (5) for the saturated water steady boiling for jet impinging on the stagnation zone.

$$q_{c,0} = 360000\left(\frac{V}{d}\right)^{1/3} \tag{5}$$

where, V is the impact velocity exited from nozzle. Eq. (5) reveals the effect of impact velocity and nozzle diameter on the CHF under atmospheric pressure and low impact velocity conditions, from where we can especially find the effect of V is positive.

It is reported that the CHF of steady boiling for circular jet impingement was up to a maximum value of 10^7 W/m^2, which is of great difficulty to increase further in the experiment [21–26]. Under steady-state heat transfer condition, the thermal conductivity of copper is 383 W/m/K, and more than 500 K/mm temperature gradient will form inside the copper conductor when the wall heat flux exceeds 2×10^8 W/m^2. Such a large temperature gradient makes it impossible to exert external heating methods for the experimental study. Therefore, the direct ohmic heating (internal heating) generated in thin resistance material charged with electricity becomes the only approach to achieve such a high heat flux. Steady boiling for high-velocity jet impinging on the stagnation zone is the best technical method to enable the heat flux of the heater to reach the theoretical ultimate CHF.

The main purpose of this study is trying to make the steady boiling CHF of jet impingement as close to the theoretical ultimate CHF (2×10^8 W/m^2) as possible, and discuss the corresponding experimental technical means. The study mainly focuses on the effect of high impact velocity on the CHF of steady boiling for high-velocity jet impinging on the stagnation zone from both the experimental study and theoretical analysis.

2. Experimental apparatus and procedure

In this study, steady heat transfer experiments were conducted for nucleate boiling regime to determine the CHF. 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 long (2 h) boiling of water in a water tank at atmospheric pressure. After deaeration, water was cooled or heated to a predetermined temperature at atmospheric pressure in the water tank. After that, the water was drained from the tank by a multistage centrifugal pump and exited from a vertical nozzle. A thermocouple is placed inside the nozzle to measure the jet temperature. The flow rate was controlled and measured by a control valve and a turbine flow meter respectively. The temperature of the exiting water was also measured by a ther-