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Effects of surface orientation and heater material on heat transfer coefficient and critical heat flux of nucleate boiling

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A B S T R A C T

External reactor vessel cooling (ERVC) is the key technology for In-Vessel Retention (IVR) to ensure the safety of a nuclear power plant (NPP) under severe accident conditions. The thermal margin of nucleate boiling heat transfer on the reactor pressure vessel (RPV) lower head is important for ERVC and of wide concern to researchers. In such boiling heat transfer processes, the reactor vessel wall inclination effect on the heat transfer coefficient (HTC) and critical heat flux (CHF) should be considered. In this study, experiments were performed to investigate the effects of surface orientation and heater material on the HTC and CHF of nucleate boiling. Copper (Cu), stainless steel (SS) as well as prototype material (SA508) of the reactor pressure vessel in the nuclear power plant were used to perform boiling tests under atmosphere pressure, respectively. The orientation angle of all boiling surfaces were varied between 0° (upward) and 180° (downward). The experimental results show that the HTC is enhanced for the downward heater surfaces ($\varphi > 90^\circ$) under the low heat flux conditions and the enhancement ratio decreases with the increase of the heat flux. In addition, the relationship of measured CHF value with the orientation angle was obtained and it shows that the CHF value changes little as the inclination angle increases from 0° to 120°, but it decreases rapidly as the orientation angle increases towards 180° for all boiling surfaces. The material effect, which indicated by thermal effusivity $\sqrt{\rho c_p k}$, on CHF is also investigated that the surface with larger thermal effusivity has the higher CHF value. In addition, the SA508 surface has the highest CHF value comparing with those of Cu surface and SS surface due to surface corrosion in the boiling process. Based on the experimental data, a correlation for CHF prediction is developed which includes the effects of surface orientation, thermal effusivity and corrosion.

1. Introduction

According to the lessons from the Three-Mile Island Unit 2 (TMI-2) accident in 1979, some researchers emphasized the importance of IVR strategy on preventing the broad spreading of radioactive waste to the environment. One method to achieve IVR is ERVC which involves flooding the reactor cavity to submerge the reactor vessel to remove the heat from the core debris under a severe accident. During this process, the heat load on the RPV lower head should not exceed the CHF. Many researchers had carried out IVR-ERVC experiments like CYBL, UPLU, SULTAN, SBLB, etc. [1–4]. The HTC and CHF are local characteristics on the RPV lower head which involves complicated two phase flow and are affected by many factors, such as inclination, surface material properties, aging, channel width, etc. In order to better understand these effects on the CHF, some separate small scale mechanistic experimental investigations have been performed.

The effect of surface orientation on HTC and CHF has been experimentally studied by many researchers and several correlations were established. Table 1 shows the experimental studies related to the effect of orientation on the water boiling CHF with the SS [5–7], Cu [8–12] and other modified boiling surfaces [13–15]. However, there are some controversies existing in different experimental results. Ishigai and Githinji [12,16], among the earliest investigators to study the orientation effect on the HTC and CHF in pool boiling, found that both HTC and CHF decreased greatly for downward facing surface comparing with upward facing surface. However, according to the experimental data of water boiling on a copper plate, Nishikawa et al. [17] concluded that the HTC increases with the increase of orientation angle in relatively low heat flux region while there is no marked effect in high heat flux region. Jung and Kim [18] studied the orientation effect on the HTC by the boiling experiment on an ITO surface and found that

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Nomenclature

z	stability factor of nucleate boiling
φ	orientation angle, °
σ	surface tension, N/m
k	thermal conductivity of liquid, W/(m K)
c_p	specific heat capacity, J/(kg K)
h_{fg}	latent heat of evaporation, J/kg
A	heated area, m^2
g	gravity acceleration, m/s^2
h	heat transfer coefficient, $W/(m^2 K)$
ρ	density, kg/m^3
V	voltage, V
I	current, A
Q_{hl}	heat loss, W
q	heat flux, W/m^2
q_c	critical heat flux, W/m^2
q_{c0}	critical heat flux at 0°, W/m^2
β	contact angle, °
δ	distance, m
U	uncertainty
T_w	wall temperature, K
T_f	liquid temperature, K
ΔT_{sat}	superheat, K
μ	dynamic viscosity, Pa s
δ_{asy}	asymptotic thickness of heater, m

Subscripts

v	vapor
f	fluid
p	pressure

Table 1
Experiments of the orientation effect on CHF (0° represents horizontally upward surface and 180° represents horizontally downward surface).

Reference	Fluid	Surface materials	Boiling state	Orientation angles
[5]	Water	SS plate	Steady saturated	135°, 150°, 165°, 176°
[6]	Water	SS plate	Steady saturated	180°
[7]	Water	SS plate	Steady saturated	0°, 30°, 90°, 120°, 130°, 150°, 174°, 176°, 178°, 180°
[8]	Water	Cu plate	Quenched saturated	90°, 135°, 150°, 165°, 170°, 175°, 180°
[9]	Water	Cu plate	Steady saturated	0°, 45°, 90°, 135°, 180°
[10]	Water	Cu plate	Steady saturated	0°, 45°, 90°, 135°, 180°
[11]	Water	Cu plate	Steady saturated	90°, 120°, 135°, 150°, 175°
[12]	Water	Cu plate	Steady saturated	180°
[13]	Water	Sintering Cu powder on Cu plate	Steady saturated	0°, 45°, 90°, 135°, 170°, 180°
[14]	Water	TiO_2 nano-coated ceramic plate	Steady saturated	0°, 90°, 135°, 170°, 180°
[15]	Water	Structured Cu plate	Steady saturated	90°, 120°, 135°, 150°, 175°

the heat transfer performance improved from 0 to 90° as a result of remarkable increases in nucleation site density and average bubble departure diameter.

Vishnev [19] proposed a correlation as shown in Eq. (1) to predict the orientation effect on CHF based on the experimental data of liquid helium boiling tests.

$$q_c = z(190-\varphi)^{0.5} h_{fg}\left(g\sigma(\rho_f-\rho_v)\rho_v^2\right)^{0.25} \tag{1}$$

El-Genk and Guo [8,20] conducted quenching experiments in water and proposed a correlation as shown in Eq. (2) to predict the orientation effect on CHF.

$$q_c = \left(0.034+0.037(180-\varphi)^{0.656}\right) h_{fg}\left(g\sigma(\rho_f-\rho_v)\rho_v^2\right)^{0.25} \tag{2}$$

Brusstar [21] investigated the surface orientation effect on CHF experimentally and theoretically. A buoyancy driven assumption was proposed and the orientation angle represents the buoyancy vector. For upward surface ($0^\circ < \varphi < 90^\circ$), the bubble could leave the surface freely, so the surface orientation will not affect the CHF. While for the downward surface ($90^\circ < \varphi < 180^\circ$), the buoyancy force will constrain the bubble on the heater surface to increase its residence time, which deceases the CHF. Thus, the correlations as shown in Eq. (3) were developed to predict the orientation effect on CHF and the predicted results matches well with their experimental data.

$$q_c = \begin{cases} q_{c0}|\sin\varphi|^{0.5} & 90^\circ < \varphi < 180^\circ \\ q_{c0} & 0^\circ < \varphi < 90^\circ \end{cases} \tag{3}$$

Liao et al. [9] performed CHF experiment on a Cu surface with water and found that the CHF changed little with the orientation angle between 0° and 90°, then it decreased fast as the orientation angle increasing from 90° to 180°. A correlation as shown in Eq. (4) was setup by fitting the experimental data.

$$\frac{q_c}{q_{c,Zuber}} = \left[-0.73+\frac{1.73}{1+10^{-0.021(185.4-\varphi)}}\right]\left[1+\frac{55-\beta}{100}(0.56-0.0013\varphi)\right] \tag{4}$$

Heater material was also thought to be an important factor affecting HTC and CHF [22–24]. Grigoriev et al. [22] investigated the heater material effect on the CHF by the experiments of liquid nitrogen boiling on different materials' surfaces and found that the CHF increased with the increase of thermal effusivity, $\sqrt{\rho c_p k}$. Westwater et al. [23] established the CHF correlation including the thermal effusivity which explained that a good thermal effusivity helps to conduct the heat away from the local dry patch and delay the occurrence of CHF.

Due to the low conductivity of SA508 (the prototype material of reactor pressure vessel), the heater surface was substituted by copper which has higher conductivity so as to reduce the difficulties when performing the full scale simulation experiments. However, such material (thermal effusivity) effect on the CHF has seldom been discussed comprehensively, especially for the water boiling on the downward surface. In order to well understand the thermal effusivity effect on the CHF and confirm how the orientation affects the HTC and CHF, three heater surface materials (Cu, SS and SA508) are used to perform the boiling experiments.