Effect of finned structure on critical heat flux (CHF) in downward-face pool boiling

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Abstract

Critical heat flux (CHF) plays an important role as the upper limit of heat dissipation process during the in-vessel reactor external reactor vessel cooling (IVR-ERVC). IVR-ERVC is regarded as a very effective way to release the decay heat after the core melt. This severe accident mitigation countermeasure has already been applied in some advanced PWRs and is considered to be used in some advanced BWRs as well. In this paper, experiments of the macro-fin structure positioned on a slope with 5° and 10° downward inclination angle were carried out. The results of the copper bar experiments were then analyzed and compared with the results obtained from a copper bare block experiments which were conducted previously at the same test facility. It was found that the CHF of the finned structure decreased compared with that of the bare surface. This shows that the current CHF data of the bare surface cannot be used directly to the design of new advanced BWRs. The hot/dry spot theory designated for the copper bar was brought up with an attempt to explain the difference of copper bare block and copper bar. Results show that using this theory can explain the decrease of CHF of the copper bar.

Keywords : Critical heat flux, Pool boiling, Down-ward face, Heat transfer, Finned structure

1. Introduction

When considering the cooling down of the reactor after core melt, in vessel retention external reactor vessel cooling (IVR-ERVC) is regarded as one of the most prominent methods and is now being widely applied by many advanced PWRs. In the case of IVR, the reactor pressure vessel (RPV) cavity is flooded with water so that the decay heat generated by the fuel can be removed by heat conduction through RPV wall. One of the priorities which demanded attentions was the critical heat flux (CHF) which limited the upper threshold of this strategy. The heat removal of downward facing surface is one of the most important features in the EVRC process (Noh et al. 2013; Chung et al. 2016). The boiling phenomena are deeply connected to the bubble behavior such as bubble generation, sliding and coalesce. It is of great importance to consider the bubble behavior during the boiling process.

Besides nuclear fields, the bubble formation is also important in many other fields such as solar storage system (Pakdaman et al. 2011). The bubble formation on a downward surface is very important for predicting the bubble behavior and is different on different materials (Wang et al. 2018). A comprehensive study on the sliding mechanism of the rising bubble under an inclined plane can be found in Maxworthy (1991). The formation of the bubble is complex as it is affected by a variety of parameters such as gas flow rate, nozzle geometries, surface morphology, and thermos physical properties of solid, liquid and gas phases. Davidson (1960) established a correlation about the departure volume using gas flow rate. Based on the research of single bubble behavior, Kandlikar (2001) proposed a method to predict the CHF and it showed good results in predicting the CHF for

surfaces of different contact angles.

As for the pool boiling experiments considering the influence of the fin, many researches have been done. One experiment performed to understand the boiling phenomenon on a fin was done by Liaw and Yeh (1994). One pin with 10 cm height was investigated and they found a significant increase in the burnout temperature. Another experiment of this kind is carried out by Guglielmini et al. (1996). An array of square fins were applied. It was found that better boiling performance was achieved with the fins compared to a plane surface. Yu and Lu (2007) also investigated the effect of an array of fins in FC-72, varying the fin spacing and length. They obtained higher CHF with longer fin length and shorter fin spacing.

Actually the IVR was designed for the advanced PWRs firstly, then this kind of method was also considered designing of advanced BWRs (Sato et al. 2009). However, one of the biggest differences between the PWR and BWR is the use of Control Rod Guide Tube (CRGT) in the lower head of RPV. This would cause very big differences to the boiling behavior in the lower head if IVR was applied. In order to investigate the effect of the extended macro structure, our experiment investigated this bar structure to address the basic problems which may occur in the downward-face boiling phenomena with an extended surface.

Macroscale pin–fin studies in downward-face conditions are rarely found in the literature. Experiments were performed in order to understand the fundamentals of the downward-face pool boiling phenomenon around a single fin. A model will also be proposed in order to explain the difference between bar structure and bare surface. It is desired that the results of the current study will provide a better understanding on this matter.

2. Experimental setups and procedure

2.1 Experimental facility

A schematic diagram for pool boiling experimental apparatus is shown in Fig.1. Distilled water was supplied into the tank and heated up by the cartridge heater. The tank was made of acrylic so that the high speed camera could be used to observe the boiling phenomenon, especially, the bubble behavior during the experiment. In the experiment, the high speed camera was operated at a resolution of 1024×1024 , 1000 fps. A data logger was connected to four thermocouples to measure the temperature, among which three were connected to the copper block, and the other one was used to measure the water temperature. A support was used to fix the tank and the inclination angle was changed by adjusting the support. In the experiment, the temperature of the water was controlled at 100 ± 0.5 °C to guarantee the saturation of the water.

Fig. 1 Schematic diagram of the experimental apparatus.

The test sections comprised a copper base attached with a copper bar and polyether ether ketone (PEEK, thermal isolation zone). The detailed geometrical information of the copper block base is shown in Fig. 2. The boiling surface of the copper was a 30 * 30 mm square. 5 Cartridge heaters (225 W power rating per heater) were inserted at the top of the copper block base as a heat source. 3 K-type thermocouples (uncertainty: ± 0.5 °C) were inserted to the bottom part of the copper block base with every 3 mm interval. And the bar has a diameter of 6 mm

and a length of 9.5 mm.

Fig. 2 Test section schematic.

2.2 Experimental procedure

Before the experiment, the surface was cleaned by both fine and coarse sandpapers (P1200 and P600), and then by acetone. The distilled water was heated up to saturated conditions under atmospheric pressure and kept for 10 min for air evacuation. During the experiment, a preheater was used to maintain a constant water temperature, and the power of the cartridge heaters was increased every 20V at rather low heat flux. When it came to 80% of CHF, it was increased every 10V until CHF conditions were reached. In terms of heat flux, it was increased about 0.04 MW/m² per step. The temperature raised gradually and if the temperature could hold on for at least 1 minute, then the images of the downward face was taken by the high speed camera. After confirming that the stable state had been reached, the next heat flux was proceeded. When the temperature of the thermocouples suddenly increased significantly (usually more than 50°C in a very short time), CHF conditions were assumed. The power was immediately shut down to prevent further damage.

2.3 Uncertainty analyses

For the data processing, the least squares method is applied in order obtain a best optimum line, so the heat flux can be calculated by the slope b (dT/dx) multiplied by the thermal conductivity k as shown in Eq. (1). The heat transfer coefficient can be calculated by the heat flux divided by the degree of superheating (ΔT) as Eq. (2). Here, all parameters are independent, so the standard deviations σq , $\sigma(\Delta T)$, and σh (Eqs. (3)–(7)) are given as follows:

$$q'' = k \frac{dT}{dx} \quad (1)$$

$$h = \frac{q''}{dT} \quad (2)$$

$$\sigma q'' = \sqrt{\frac{s^2 n}{\sigma}} \quad (3)$$

$$\sigma(\Delta T) = \sqrt{\frac{s^2 \sum T_i^2}{\sigma}} \quad (4)$$

$$\sigma h = \sqrt{\left(\frac{\partial h}{\partial(\Delta T)} \sigma(\Delta T) \right)^2 + \left(\frac{\partial h}{\partial q} \sigma q \right)^2} \quad (5)$$

$$s = \sqrt{\frac{1}{n-2} \sum (y_i - (bx_i + a))^2} \quad (6)$$

$$\sigma = n \sum x_i^2 - (\sum x_i)^2 \quad (7)$$

Where T_i (y_i) is the temperature at different locations i ; x_i , the interval distance from the boiling surface; k , the thermal conductivity; and n , the number of temperature measurement points (three thermocouple positions). The maximum uncertainty of CHF obtained in the experiment was no more than 5%.

3. Experimental results and discussions

CHF experiments were conducted with copper bar test section, and compared to the experimental results of copper bare block (Gong et al. 2017).

3.1 Boiling curves analysis

By changing the set-up of the test section, the experiments were conducted under downward inclination angle Θ of 5° or 10° .

Fig. 3 Images of copper bar surface under an inclination angle of 5° at a low heat flux (0.01 MW/m^2).

Fig.4 Boiling curve of copper bar experiment.

In this study, high-speed camera was applied to capture the surface image. Fig. 3 (a-d) shows the images of the

copper bar surface at 5° under a very low heat flux (0.01 MW/m^2). The images of the rather low heat flux were shown because in high heat flux conditions, the surface was covered by a great amount of bubbles, which was very difficult to analyses. Many small bubbles generated on the heating surface, and with further heat supplied, small bubbles grew bigger. Some of the small bubbles coalesced and became big bubbles. As the bubbles continued to coalesce, they eventually became vapor film large enough to escape from the surface.

Fig. 5 Comparison of copper and copper bar boiling curves.

Fig. 4 shows the boiling curve of the copper bar at a downward inclination angle of 5° and 10° . Obviously, CHF with an inclination angle of 10° is higher than that of the 5° because vapor is easier to escape from the surface. Fig. 5 shows the comparison of the boiling curves of copper bare block and copper bar. Comparing the copper bar CHF (0.11 MW/m^2 for 5° and 0.24 MW/m^2 for 10°) with the copper block CHF (0.25 MW/m^2 for 5° and 0.47 MW/m^2 for 10°), we can conclude that the CHF of the copper bar is much lower than that of the copper bare surface.

3.2 Discussion

Though many pursuits have been devoted to understanding the CHF phenomena, the mechanism of CHF yet remains unknown. Many researchers have put forwards different theories to explain the CHF. For example, Zuber (1959) proposed the hydrodynamic theory by assuming that the departure of nucleate boiling (DNB) was caused by the vapor and liquid interaction.

One of the most adopted theories to explain CHF is the hot/dry spot theory. This theory assumed there were two kinds of bubbles generating from nucleate sites on the surface. One kind of nucleation sites is called reversible spots meaning that rewetting occurs after bubble departure, which will not cause DNB. The other kind is the irreversible spots meaning that rewetting will not occur and will cause burnout (Theofanous et al. 2002).

Based on this theory, many correlations have been proposed to obtain the CHF.

Among the correlations, one of the most widely used is the Kandlikar (2001) correlation for the pool boiling of the copper bare block:

$$q_m = h_{fg} \rho_g^{\frac{1}{2}} \left(\frac{1 + \cos \beta}{16} \right) \left[\frac{2}{\pi} + \frac{\pi}{4} (1 + \cos \beta) \cos \theta \right]^{\frac{1}{2}} [\sigma g (\rho_l - \rho_g)]^{\frac{1}{4}} \quad (8)$$

Where q_m is the CHF, h_{fg} is the latent heat, ρ_l and ρ_g are the density of liquid and gas phase, respectively, σ is the surface tension, β is the contact angle, and θ is the upward inclination angle.

Fig. 6 Forces due to surface tension, gravity and momentum acting on a bubble parallel to the heater surface.

According to the Kandlikar theory, CHF is related to contact angle, inclination angle and so on. This model derived from the analyses of single bubble attached to the heating surface as shown in Fig.6 (a). The main forces acting on the left half of the bubble are analyzed as follows. The excessive pressure inside the bubble under a quasi-static equilibrium state is able to sustain the necessary curvature of the interface at the departure condition. At low heat fluxes, the bubble departed at certain size as governed by the forces due to inertia, pressure and buoyancy.

Similar to the bare surface bubble analyses, the model with a bar on the surface is built. As shown in Fig.6 (b), the bubble is deformed with the presence of the bar. The biggest difference is the surface tension force generated on the bar contacting area because of the bar structure.

For a unit length in the direction normal to the plane, the forces $F_{s,1}$, $F_{s,2}$ and $F_{s,3}$ are given by

$$F_{s,1} = \sigma, F_{s,2} = \sigma, F_{s,3} = \sigma \sin \beta \quad (9)$$

Where σ is the surface tension force.

For the resulting force F_M due to the momentum change

$$F_M = \left(\frac{q_l}{h_{fg}} \right)^2 \frac{H_b}{\rho_g} \quad (10)$$

q_l is the heat flux due to evaporation per unit and H_b is the bubble height. In the current bar case, the relationship between q_l and $q_{m,bar}$ is a little bit different with the bare surface one. The main reason is that the bubble generated around the bar was also influenced by the heat flux generated from the bar. As a first step research, we assume that the influence area was twice as the bare surface case. Thus for the bar structure,

$$q_{m,bar} = \frac{1}{2} \frac{(1+\cos\beta)(D_{ave}/2)(\pi D_{ave}/2)}{(\pi/4)(2D_b)^2} q_l = \frac{(1+\cos\beta)}{32} q_l \quad (11)$$

Where D_b is the bubble diameter.

The gravity force is

$$F_G = \frac{1}{2} g (\rho_l - \rho_g) H_b^2 \cos\theta \quad (12)$$

According to Kandlikar theory, if we still assume

$$H_b = \frac{D_b}{2} (1 + \cos\beta) \quad (13)$$

For the force balance at CHF point,

$$F_M + F_{s,3} = F_{s,1} + F_{s,2} + F_G \quad (14)$$

Combination of Eq. (9) through Eq. (14) yields

$$q_{m,bar} = h_{fg} \rho_g^{\frac{1}{2}} \left(\frac{1+\cos\beta}{32} \right) \left[\frac{2\sigma(2-\sin\beta)}{D_b(1+\cos\beta)} + \frac{D_b}{4} (\rho_l - \rho_g) g (1 + \cos\beta) \cos\theta \right]^{\frac{1}{2}} \quad (15)$$

We still have an unknown parameter D_b in Eq. (15). Fortunately, according to the analysis of Kandlikar (2001), D_b is assumed to be half of the wavelength of the Taylor instability of a vapor film over the heater surface by (Zuber, 1959).

$$\lambda_T = C_1 2\pi \left(\frac{\sigma}{g(\rho_l - \rho_g)} \right)^{1/2} \quad (16)$$

The value C_1 is from 1 to $\sqrt{3}$. In the bar model, C_1 is taken as 1 and $D_b = \lambda_T/2$. CHF of the copper bar can be illustrated as

$$q_{m,bar} = h_{fg} \rho_g^{\frac{1}{2}} \left(\frac{1+\cos\beta}{32} \right) \left[\frac{2\sigma(2-\sin\beta)}{\pi(1+\cos\beta)} + \frac{\pi}{4} (1 + \cos\beta) \cos\theta \right]^{\frac{1}{2}} [\sigma g (\rho_l - \rho_g)]^{\frac{1}{4}} \quad (17)$$

Unfortunately, these correlations are only suitable within an inclination angle from 0° – 110° ; however, the inclination angle in this study ranges from 170° – 175° . The reason that this model cannot be applied to higher inclination angle is that flow hydrodynamics (gravity effect and bubble coalesce) and heater size effects have a big influence under higher inclination angle, which is difficult to model using the current assumptions.

One possible way to solve this problem is to combine this equation with the effects of orientation correlation. And this method has been described in the previous work (Wang et al. 2018).

Three different regions: upward-facing (0 – 60°), near-vertical (60 – 165°), and downward-facing (165 – 180°) was characterized by the different vapor behavior observed during the pool boiling experiment. Different CHF trigger mechanism was assumed in different regions (Howard and Mudawar, 1999).

Vishnev (1973) was among the first who were trying to establish a correlation with the orientation effect taken into consideration. El-Genk and Guo (1993), Chang and You (1996), and Brusstar and Merte (1997) also developed their own empirical models. These models take the following forms.

Vishnev model:

$$\frac{q_m}{q_{m,0^\circ}} = \frac{(190-\theta)^{0.5}}{190^{0.5}} \quad (18)$$

Chang and You model:

$$\frac{q_m}{q_{m,0^\circ}} = 1.0 - 0.00012\theta \tan(0.414\theta) - 0.122 \sin(0.318\theta) \quad (19)$$

Brusstar and Merte model:

$$\frac{q_m}{q_{m,0^\circ}} = (\sin\theta)^{0.5}, 90^\circ - 180^\circ \quad (20)$$

El-Genk and Guo correlations:

$$q_{CHF}(\theta) = C_{CHF}(\theta) \rho_g^{1/2} h_{fg} [\sigma g (\rho_l - \rho_v)]^{1/4} \quad (21)$$

$$C_{CHF}(\theta) = 0.034 + 0.0037\theta^{0.656} \quad (22)$$

$q_{m,0^\circ}$ stands for the CHF value of the heater oriented in the horizontal upward-facing position. θ stands for the

downward inclination angle and $\theta = 180^\circ - \theta$.

Fig.7 Comparison of experiment results with correlations.

Fig. 8 Images of copper bar surface and copper surface at a low heat flux (0.01 MW/m^2).

Combining Kandlikar correlation (Eq.(8)) for the copper bare block and Eq.(17) for the copper bar with the above orientation effect correlations yields the results presented in Fig. 7. Chang correlation over predicts CHF while Brusstar correlation fits the data best.

Actually this kind of effect can be also demonstrated by the images. On the bare surface like Fig.8 (a), the bubbles can form bigger bubbles and bubbles bigger than a certain size can escape from the surface easily. However, on the finned surface, the bubbles will be attracted to the bar due to the surface tension. Thus the difficulty of bubble escaping will result in the earlier CHF.

In Khan et al. (2018), the effect of downward-facing finned surface on CHF for flow boiling was investigated.

Both positive and negative effects on CHF were found. The increase of CHF in the high mass flux conditions was attributed to the increased heat transfer and turbulence in the wake region. In the relative low mass flux condition, the reverse influence of CHF was contributed to the bubble accumulation in the wake region. In our experiment, it is also found that the bubbles are prone to attach the bar structure in the wake region, which suggests that the bubbles are easy to be influenced by the bar, and thus leading to an earlier CHF.

4. Conclusions

The application of cavity flooding is considered as one of the counter measurements of core melt. There has been many studies for nucleate boiling in PWRs. However, the study for BWR case is rather scarce. This paper introduced an experiment concerned with the downward boiling using bar structure. Results were analyzed with comparison to the bare surface results. Detailed images of each surface were also obtained and analyzed. The conclusions are as follows:

- (1) The copper bar CHF's under both 5° and 10° were much lower than those of the copper bare block.
- (2) The hot/dry spot theory for the copper bar was brought up and it could explain the difference in CHF between copper bare block and copper bar well.

As the copper bar exhibits lower CHF than bare surface in some cases, it is important to consider the effect of bar structure in the application of cavity flooding of the BWRs. More attention should be paid because there is a possibility that an earlier CHF will occur due to the existence of bar structure in the lower plenum of BWRs.

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