Thermal-Hydraulic Effects of Stud Shape and Size on the Safety Margin of Core Catcher System

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1. Introduction

As the number of nuclear power plants increases and they are located close to highly populated area, the public are more concerned about nuclear safety. While the installation of the nuclear power plants renders enormous economic benefit, potential radiological risks to the public due to the hypothesized severe accident cannot be ruled out. Against the potential severe accidents, a nuclear power plant is equipped with diverse engineering safety features or mitigation systems that can be used under the severe accidents conditions. Generally, many nuclear power plants adopt the in-vessel retention (IVR) and/or external reactor vessel cooling (ERVC) strategies. With the ERVC strategy, an additional system (core catcher system) to catch molten core penetrating the reactor pressure vessel (RPV) was proposed for advanced light water reactor. The newly engineered corium cooling system, that is, an ex-vessel core catcher system has been designed and adapted in some nuclear power plants such as VVER-1000, EPR, ESBWR, EU-APR1400 to mention a few. For example, Russia adopted a crucible-type core catcher for VVER-1000 [1]. On the other hand, a way to catch melt spreading is adopted by several countries, such as EPR in France, ESBWR in USA, ABWR in japan, and EU-APR1400 in Korea [2-5]

In Korea, the core catcher system has been designed and implemented for the European Advanced Power Reactor 1400 (EU-APR1400) to acquire a European license certificate [6,7]. It is to confine molten materials in the reactor cavity while maintaining a coolable geometry in case that RPV failure occurs. The core catcher system consists of a carbon steel body, sacrificial material, protection material and engineered cooling channel. The engineered cooling channel was designed to remove sensible heat and decay heat of the molten corium using cooling water flooded from the In-Containment Refueling Water Storage Tank (IRWST) by gravity. A large number of studs are placed in the cooling channel to support the core catcher body [8]. While installation of the studs is unavoidable, the studs tend to interfere in the smooth streamline of the core catcher channel. The distorted streamline could affect the overall thermal-hydraulic performance including two-phase heat transfer coefficient and critical heat flux (CHF) of the system. Thus, it is of importance to investigate the thermal-hydraulic effects of studs on the coolability, especially the CHF of the core catcher system.

With aforementioned importance, pool boiling experiments were carried out with stud shape of, rectangular, cylinder, and elliptic and for stud sizes of 10, 15, 20, and 25 mm under the condition of atmospheric saturated water. A visualization work was adopted to collect boiling image using a high-speed camera during the tests. A particular attention was focused on observing local vapor behavior around the studs and finding any hot spots, where the vapors are accumulated. The occurrence of the CHF is anticipated at the back side of the studs. The visual observation and CHF measurements indicate that the effect of studs on the performance of boiling heat transfer is significant.

2. Background

Until now, many researchers have made significant efforts to interpret CHF mechanism for pool boiling by correlating the experimental data. Among them, Vishnev (1973) first proposed that the effect of surface orientation on the pool boiling CHF with a small plate and developed the following CHF correlation [9].

$$\frac{q_{CHF}}{q_{CHF,0}} = \frac{(190-\theta)^{1/2}}{190^{1/2}} \tag{1}$$

As shown in Eq. (2), El-Genk and Guo (1993) tried to correlate the effect of the heater surface inclination on the pool boiling CHF using a copper disk having a thickness of 12.8 mm and a diameter 50.8 mm with saturated water in the near atmospheric pressure [10].

$$q_{CHF} = [0.034 + 0.0037(180-\theta)^{0.656}]\rho_g h_{fg} \times [\sigma g(\rho_f - \rho_g)/\rho_g{}^2]^{1/4} \tag{2}$$

Monde et al (1982) defined the following CHF correlation (Eq. 3) with a copper surface of 20×50 mm^2 in width and length respectively and with gap sizes ranging from 0.45 to 7.0mm [11].

$$q_{CHF} = \frac{0.16 h_{fg}\rho_g[\sigma g(\rho_f - \rho_g)/\rho_g{}^2]^{1/4}}{1 + 6.7\times10^{-4}(\rho_f/\rho_g)^{0.6}(L/s)} \tag{3}$$

Kim et al (2005) further developed a CHF correlation by using the experimental results with the inclined rectangular channel and gap size from slight modification of Monde et al.'s correlation [12], and resulting correlation is shown in Eq. (4)

$$\frac{q_{CHF}}{\rho_g h_{fg}} = \frac{0.17[\sigma g \sin\theta(\rho_f - \rho_g)/\rho_g{}^2]^{1/4}}{1 + 6.8\times10^{-4}(\rho_f/\rho_g)^{0.62}(D_h/s)} \quad (4)$$

where, D_h is the equivalent heated surface diameter, which considers effect of heater size and calculated by the following Eq. (5).

$$D_h = \frac{2wl}{w+l} \quad (5)$$

where, w and l are width and length of the heater, respectively.

As such, effects of the heater surface orientation and gap size on the pool boiling have been studied by some researchers to investigate the complexity the CHF triggering mechanism. However, any research relevant to the effect of channel blockage on the CHF has not been reported anywhere. So the major objective of this study is to investigate the effect of studs on the CHF using the scaled-down core catcher cooling channel under the atmospheric saturated pool of water.

3. Experiments

3.1 Experimental apparatus

A photo of the pool boiling apparatus used in this experiment is presented Fig. 1. The experimental apparatus consists of isothermal bath, a high speed camera, data acquisition system, and test section. In addition, a schematic diagram of the test section is shown in Fig. 2. A test specimen made of stainless steel grade 304 (SS304) was selected as test heater. The test section was designed to depict a partial region of the prototypical core catcher channel. Dimension of the channel including two studs is 99×49×10 mm^3 in length, width, and height, respectively and its schematic is shown in Fig 3. The core catcher channel was designed to be inclined at an angle of 10° from the downward-facing horizontal (0°) location to escape the vapor [5]. For the purpose of insulation of heat transported through the upward direction, a 10-mm thick peek block was installed on the heating surface. To measure the temperature and to detect occurrence of the CHF, K-type thermocouples are inserted into the hole of the peek block at four different locations of the back of the studs and sides of the first stud [13]. Each end side of the heater is connected with copper electrodes and directly heated using a DC power supply with allowable maximum capacity of 30V-2500A. To visualize the vapor behavior, windows made of polycarbonate are installed on each side and bottom.

3.2 Experimental procedures

The experiments were conducted with following procedures. Prior to each test, the heater surface was polished using acetone. To keep the steady thermodynamic state of saturated water at atmospheric pressure, the preheaters equipped in the isothermal bath were used for approximately 30 minutes prior to reading the data. Power input was gradually increased in step of 10 kw/m^2 until heat flux reached 70% of the anticipated CHF. Close to the CHF, smaller heat flux of about 5 kw/m^2 was applied to accurately capture the CHF. The CHF was defined at the point where any abrupt temperature increase of the heated surface occurred. In addition to the CHF measurement, this study also investigated nucleate boiling phenomena with the presence of studs. Thus abundant high-speed boiling images were collected from initiation of the nucleate boiling to the vicinity of the CHF using the high speed camera.

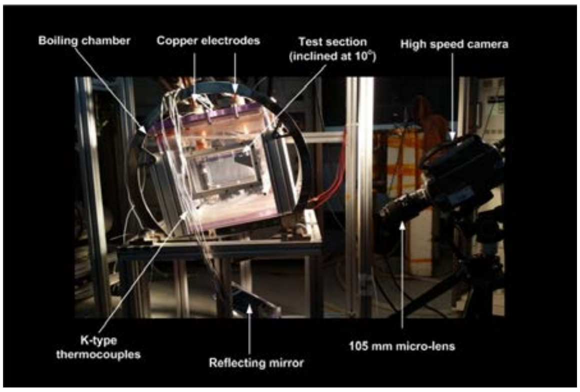

Fig 1. Photo of pool boiling apparatus

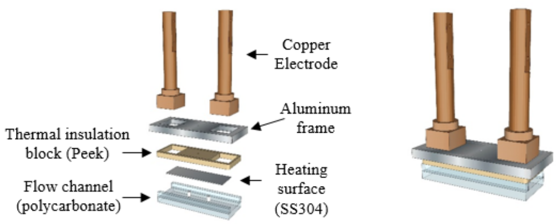

Fig. 2. Schematic diagram of the test section

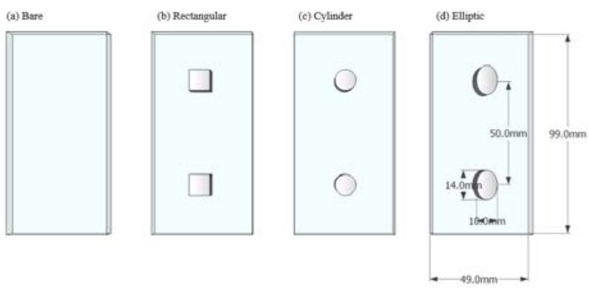

Fig. 3. Schematic diagram of Stud shapes

3.3 Experimental conditions

In the previous study, it was confirmed that different flow patterns were generated with different stud shapes

[13]. However it was challenging to observe any deterministic effect by studs' shape because stud size was similar to the vapor size. In order to resolve this issue, enlarged stud's size was considered and various stud sizes were prepared as shown in Fig. 4. The CHF tests were performed with various stud shapes and sizes in a pool of saturated deionized (DI) water at atmospheric pressure. Experimental conditions applied are summarized in Table 1.

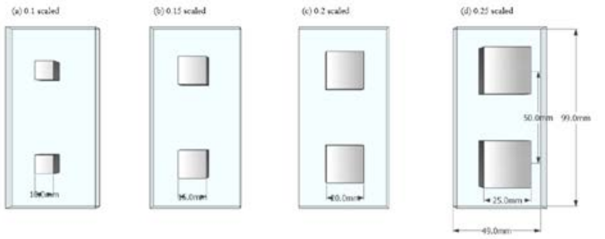

Fig. 4. Schematic diagram of Stud sizes

Table 1. Experimental condition

Test heater material	SS304
Test condition	Saturated at atmospheric pressure
Fluid	DI water
Stud shapes	Rectangular Cylinder Elliptic
Stud size (mm)	10, 15, 20 , 25
Stud material	Aluminum

4. Results and Discussion

Through the literature review, previous CHF data without any studs have been searched and summarized in Table 2. In the present study, the CHF without studs was measured as approximately 156 kW/m^2, which is lower than the CHF value predicted by El-Genk et al.'s correlation [10], by Yang et al. [14], and Kim et al. [12]. This could be due to the effect of larger heater area of wider and longer heaters compared to the smaller test sections used in other studies [10, 12, 14]. It is generally known that the heater size affects the CHF value. As the heater size is larger, the CHF value tends to decrease because the increase of wavelength is likely to reduce the number of wetting fronts available for liquid replenishment of the heater surface. In addition, the wider heater hinders the bubble escape which may be another factor responsible for the lower CHF value of current study. In this study, to simulate the cooling channel of the ex-vessel core catcher, the test section was made in the gap size of 10 mm, whose structure can also restrict the vapor behavior compared to the vapor behavior with the open periphery and thus, the vapor appears to be stagnated without effective escape. This could be additional explanation for the lower CHF value compared to the open periphery [12].

Major objective, however, is the relative CHF value due to the presence of studs. With various stud shape and size, CHF values were measured and the results are plotted in Fig. 5. With the presence of studs, the CHF value was measured lower than the CHF value without studs. The reduction ranges from 18 to 55%, which is significant penalty for the safety margin of the cooling channel. Through the visualization study, it was clearly observed that these studs are likely to hinder smooth flow in the channel and the vapors were accumulated at the back side of the studs. The resulting distorted streamline and accumulated bubbles could induce premature CHF. For more detailed analysis, the CHF decreases as the studs' size becomes larger. Especially, between 20 mm and 25 mm, the CHF decreased drastically. Therefore it is concluded that there is a significant effect of channel blockage on the CHF and the effect becomes pronounced with the larger stud.

Table 2. CHF value comparison

	CHF value (kW/m^2)	Test Heater Dimension Width × Length (Thickness) (mm)	Test Heater Material	Inclination Angle (deg)	Working Fluid	Gap size	Boiling State
Guo and El-Genk [10]	430.2	50.8 diameter (12.8)	Copper disk	10°	Water	Open periphery	Quenched; saturated pool boiling
Yang et al [14]	469	40 × 150 (2)	SS304	0°	Water	Open periphery	Steady; saturated pool boiling
Kim et al [12]	793.1	15 × 35	Copper block	10°	Water	10mm	Steady; saturated pool boiling
	1108	15 × 35	Copper block	10°	Water	Open periphery	Steady; saturated pool boiling
Present	156	49 × 99 (2)	SS304	10°	Water	10mm	Steady; saturated pool boiling

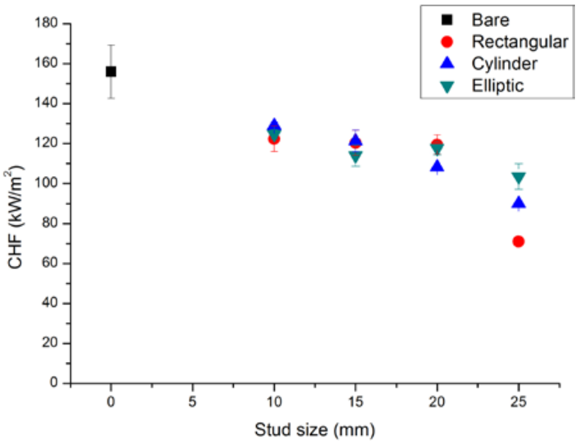

Fig. 5. CHF value with respect to the stud shape and size.

During CHF measurement, boiling phenomena were observed according to the studs' shape and size using a high-speed camera. The visualization results are represented in Fig. 6 and 7.

Figure 6 shows the visualization with the rectangular stud for three different sizes. As the stud size becomes larger, CHF data decreases. Phenomenologically it is due to the more pronounced vapor accumulation at the back side of the studs. These vapor behavior could induce premature heatup and temperature excursion and thereby the earlier CHF.

Given the same size of the stud, the CHF value with the elliptic stud resulted in the highest among tested shapes. It may be induced that elliptic shape is more likely to form smoother flow in the channel. At the back side of the studs, the less vapor accumulation was observed compared to rectangular and circular studs. As the prototypical stud size considered for the EU-APR1400 is about 10 cm, effect of stud size for the real application needs to be evaluated more systematically.

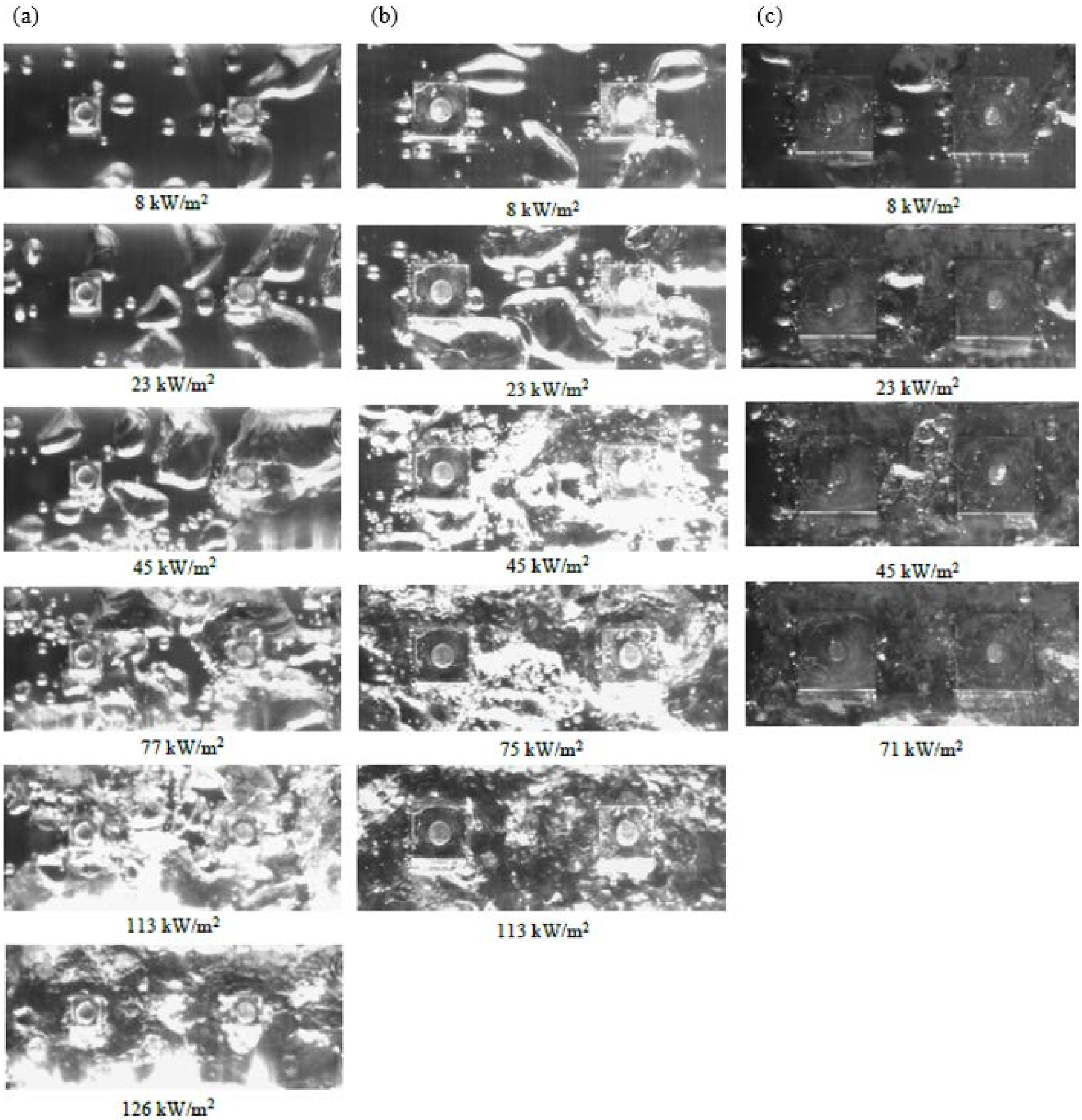

Fig 6. Visualization on the rectangular stud; (a) 10 mm, (b) 15 mm, and (c) 25 mm

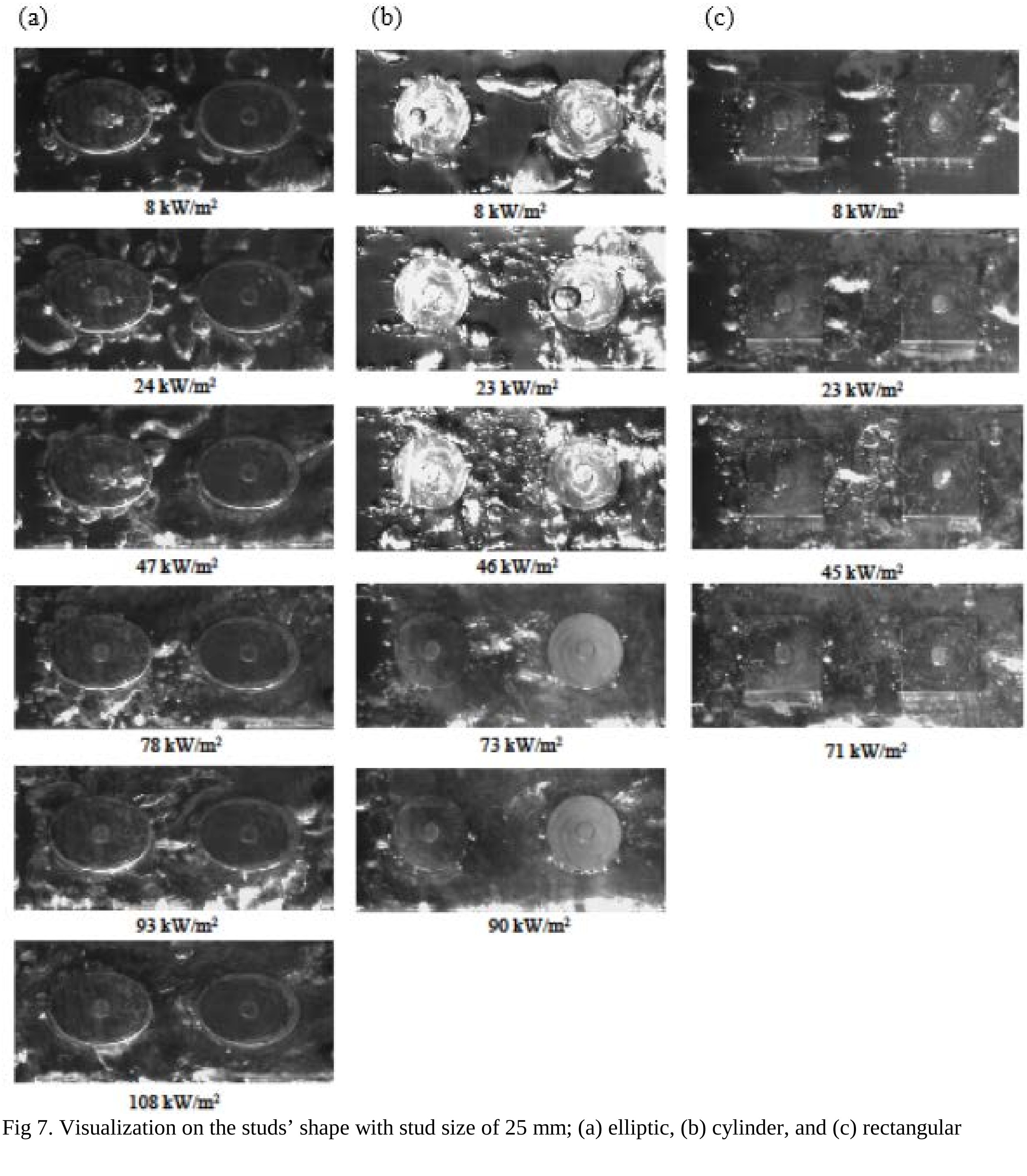

Fig 7. Visualization on the studs' shape with stud size of 25 mm; (a) elliptic, (b) cylinder, and (c) rectangular

5. Conclusion

In this work, an experimental study has been conducted to investigate the effects of stud shape and size on the pool boiling CHF of saturated water under the atmospheric pressure. The major conclusions from this study are summarized as follows.

(1). The experimental result confirmed that the installation of the stud influenced the CHF value due thermal-hydraulic restriction. With the presence of studs, the CHF value was measured lower than the bare specimen up and the reduction ranged from 18% to 55% depending on the stud shape and size.

(2). It was observed that CHF data generally decreases as the stud size becomes larger. Especially, when the size of the studs was 25 mm, the CHF value drastically decreased in all studs' shape.

(3). At the stud size of 25 mm, the stud shape affected the CHF value significantly. The CHF with the rectangular stud was the lowest among the other shape tested and relative reduction is about 21-30%.

(4). As the prototypical stud size considered for the EU-APR1400 is about 10 cm, effect of stud size for the real application needs to be evaluated more systematically.

Acknowledgements

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