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Flow boiling heat transfer on downward-facing coated large surface of inclined channel wall

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1. Introduction

Severe accident may lead to severe damages on the reactor vessel, containment, and ultimately outside environment. in-vessel retention by external reactor vessel cooling (IVR-ERVC) and/or an external core catcher system are considered as a countermeasure to mitigate the severe accident by natural circulation flow of water [1]. Therefore, knowledge on the cooling performance of those systems are essential.

The heating and cooling surface area in the nuclear power plants is generally very large including IVR-ERVS and core catcher. In addition, the geometry is quite unique depending on the type of nuclear power plant. Since the geometry and size of the heating wall has a significant effect on the heat transfer performance, it is important to know the cooling performance in the reactor scale heating system [2,3].

Surface modification is one of the most practical ways to enhance the boiling heat transfer and CHF in the heat transfer system. Microporous coating technique has been investigated for a long time to enhance the heat transfer performance [4]. The implementation of the microporous coating on the surface of the reactor lower head and/or core catcher plate have been considered, as well. However, most of the preliminary studies using microporous coating are performed on relatively small heating surface area. So, the application of coated surface to the reactor scale should be considered taking account for scale effects such as vapor accumulation by stratification.

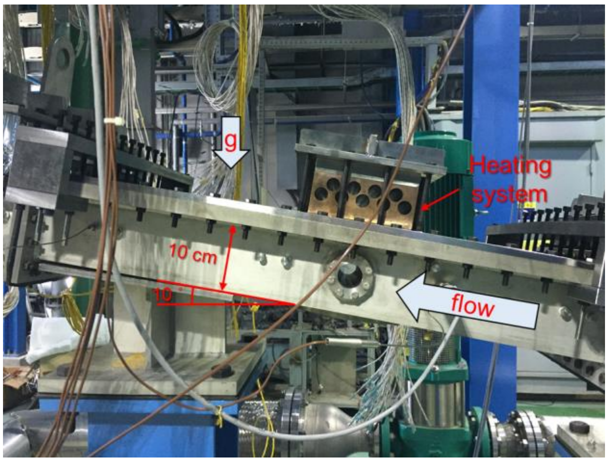
In this study, surface of downward-facing large and thick heater block was coated by thermally conductive microporous coating (TCMC) technique [5]. Flow boiling experiment was carried out in both plain and coated surface to observe the heat transfer enhancement on the microporous coated large surface.

2. Experiments and results

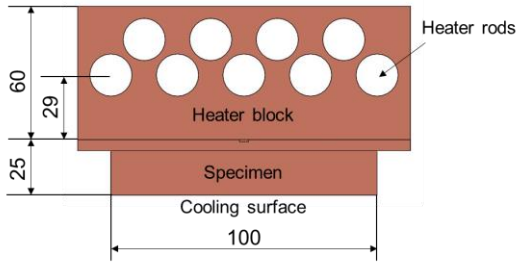
The experimental program is designed to observe the heat transfer performance on the microporous coated surface of a large and thick heater block. In this section description of the experimental facility, test program and discussion of the results are given.

2.1 Experimental setup

The test channel was established by modifying the steam-water experimental facility which simulates the core catcher system for EU-APR1400. Downward-facing heated surface is cooled by a water through the 10° inclined channel shown in Fig. 1 (a). The cross section of the channel is 100 mm height and 300 mm width. Water flows following the arrows in the Fig. 1 (a), and heat exchanger and pump allow to control the inlet subcooled temperature and the liquid mass flow rate respectively. Dimensions of the specimen and heater block made of copper are depicted in Fig. 1 (b). Heater surface area is 120 mm × 300 mm covering the entire width of the coolant channel. The bottom of the specimen came into contact with water, and the rest of the heating block and specimen were all insulated. A couple of K-type thermocouples were installed inside of the center of the specimen, 1 mm and 5 mm distance from the cooling surface to measure the surface temperature.



(a)



(b)

Fig. 1. Experimental apparatus (a) test section (b) Side view of the heating system, and specimen (dimensions in mm).

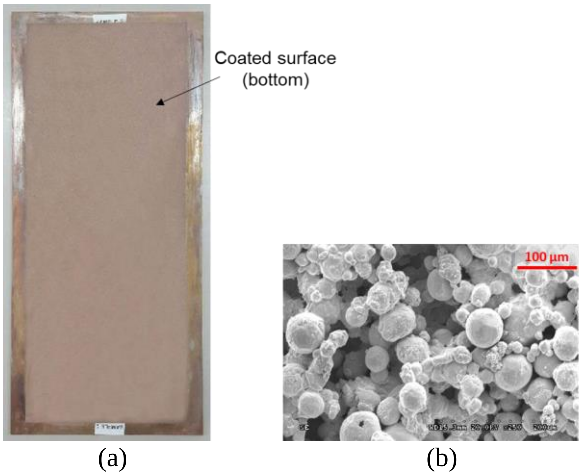


Fig. 2. Microporous coated (TCMC) surface
(a) Bottom view of the specimen (b) SEM image of TCMC [5]

A thermally-conductive microporous coating (TCMC) was fabricated on the 120 mm × 300 mm of large copper surface successfully (Fig. 2). The detailed fabrication process is provided in by Kim et al. (2010) [4]. 53-88 µm of copper powder size and 245 µm of coating thickness was chosen, which shows the best heat transfer performance in the preliminary research.

2.2 Experimental program and data processing

Experimental cases in the test program are shown in Table I. The experiments were carried out rates in both plain and TCMC coated surface in various subcoolings and flow rates. Heat flux increases gradually until CHF occurs or heating system is limited by temperature limitation.

Table I: Experimental cases

Surface type	Subcooling [℃]	Mass flux [kg/m^2·sec]
Plain surface and TCMC coated surface	10	44
	10	107
	10	180
	28	107
	28	180
	45	180

Heat flux is calculated by total supplied power divided by cooling surface area. Wall temperature is determined by linearly extrapolating two temperatures positioned at 5 mm and 1 mm distance from the cooling surface. Temperatures and supplied power were acquired in 1 Hz, and averaged in 120 seconds after steady state is accomplished. Each data is calculated by below equations:

$$q'' = Q_{total} / A \tag{19}$$

$$T_w = T_H - \frac{T_H - T_L}{L_H - L_L} L_H \tag{20}$$

$$h = \frac{q''}{T_w - T_{sat}} \tag{21}$$

2.3 Heat transfer enhancement

Boiling curves in every test cases are shown in Fig. 3. Boiling curves in each plain and coated surface show that every curve eventually converges into a single curve regardless of the flow rate and inlet subcooling. At the converged fully-developed nucleate boiling curve, nucleate boiling heat transfer is superior to dominate the entire heat transfer process.

Between the boiling curves in various flow rates, no recognizable difference was found in each surface when liquid flow velocity varies in the rage less than ~0.2 m/s (180 kg/m^2·s). On the other hand, subcooling effect on the boiling curve is relatively distinct. In the low heat flux level, both plain and coated surface followed nearly same curve before the curves met the fully-developed nucleate boiling curve. When nucleate boiling became effective, the curve followed fully-developed nucleate boiling curve. Nucleate boiling is activated at the lower heat flux in the microporous coated surface than the plain surface.

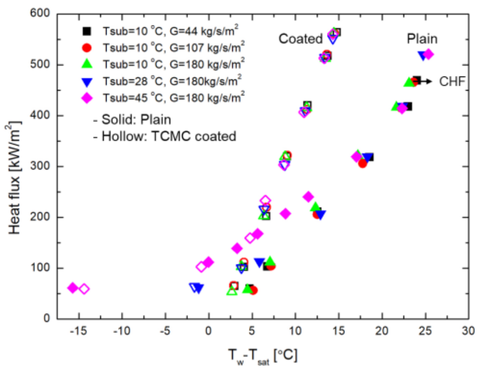


Fig. 3. Boiling curves in all test cases

Between fully developed nucleate boiling curves in Fig. 3, apparent heat transfer enhancement was observed in a microporous coated surface. About 2 times higher heat transfer coefficient was observed at 420 kW/m^2 heat flux level. heat transfer enhancement at the coated surface is clearly contributed by boiling heat transfer enhancement, since flow rate has almost no effect on the heat transfer.

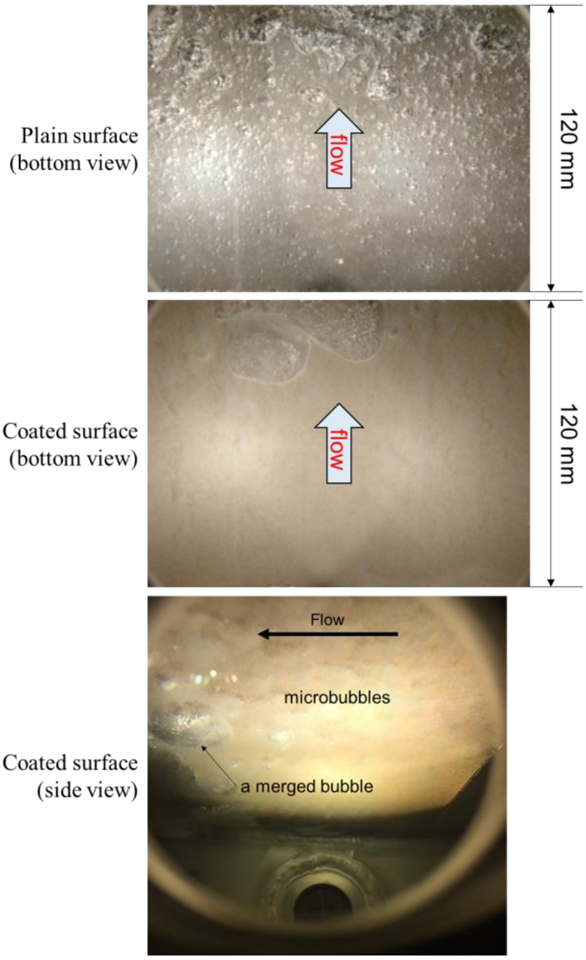


Fig. 4. Boiling phenomenon on plain and coated surface under 500 kW/m^2 in 28 ℃ subcooling condition.

Nucleate boiling phenomena on the surfaces are visualized in Fig. 4. In the coated surface, microbubbles like foggy smog are generated from the great number of nucleate sites. These large amount of microbubbles augments nucleate boiling heat transfer by activating nucleation sites. In addition, microbubbles could enhance the convective heat transfer by micro-convection initiated from the higher inertia of the departing bubbles with high frequency [4]. In this study, microbubbles generation is visualized very clearly on the large surface in the slightly subcooled liquid which leads to the higher heat transfer performance.

CHF occurs only at the plain surface in nearly saturated water, while coated surface could not reach to the CHF level until 600 kW/m^2 due to the temperature limitation of the heater rods. Approximately 450 kW/m^2 of CHF was obtained at slightly inclined (10°) downward-facing plain surface.

2.4 Comparison with preliminary researches

Fig. 5 shows the boiling curves comparison to the preliminary researches using small size heaters (10 mm × 10 mm) [5,6]. The previous studies were performed in the pool with saturated water, while the present study was carried out in the channel with low flow rate at almost saturation water (T_{sub} = 10 °C). Since the present study shows that in this experimental conditions flow effect on the heat transfer was negligible, and the near wall liquid was almost in saturation condition, present study was able to be directly compared to the previous studies [5, 6]. HTCMC is microporous-coating technique similar to the TCMC coating, but attaches micro particles by high temperature sintering method rather than using solder and solvent to reduce the thermal resistance.

In the 170° inclined large heater, TCMC coated surface shows 2 times enhancement in comparison to the plain surface, whereas 4 times enhancement is achieved in upward facing small heater.

In the large heating surface, since liquid supply to a nucleate site from the bulk environment is obstructed by the side bubbles, the large surface is rather hard to be wetted. In addition, the supplied liquid is superheated due to the heated near surface, so the liquid temperature wetting the surface is higher at the large surface than small surface. Consequently, heat transfer rate tends to decreases on the large heating surface.

When we adopt the heat transfer enhanced surface in a large heating area such as reactor system, heater size effect should be considered together. The results on the downward-facing surface of large heater block could directly be used to the core catcher system. More specific parametric studies are required in the future for comprehensive understanding of the boiling phenomena on the large heating surface.

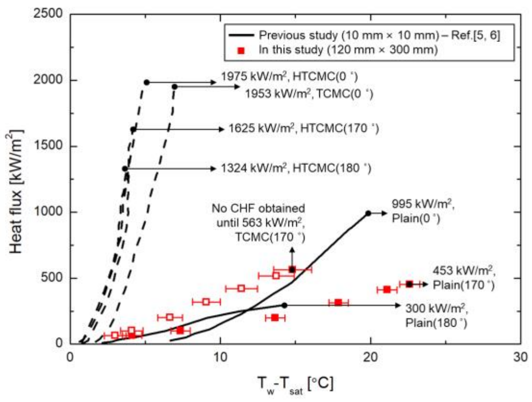


Fig. 5. Boiling curves comparison to the large and small heater. (TCMC, HTCMC: microporous coated surface)

3. Conclusions

In this study, thermally conductive microporous coating (TCMC) was applied successfully on the large surface. Flow boiling experiment was carried out using plain and microporous coated surface of a large and thick heater block in various flow rates and inlet subcoolings.

TCMC surface showed about 2 times heat transfer enhancement under the 10 ° downward-facing large surface. Large amount of microbubbles was observed in TCMC surface by high speed camera visualization, which leads to nucleate boiling heat transfer enhancement.

In downward-facing heated condition, CHF was obtained only at the plain surface under about 450 kW/m^2 heat flux in nearly saturated liquid, while TCMC surface could not reach to the CHF level until 600 kW/m^2. The CHF level from large surface was comparable to the previous researches, but heat transfer rate decreases. Further researches are required to analyze the size effect the heater.

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