Film boiling on porous layered brass sphere during quenching

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1. Introduction

Fluid (liquid or gas) can afford to be permeable into porous layer on heat transfer surface and this phenomenon significantly affects phase-change heat transfer, especially boiling [1]. Recently, realistic consideration of thermal-hydraulic analysis at nuclear safety was re-highlighted because of Corrosion Residual Unidentified Deposition (CRUD) formation at fuel cladding during normal operation in Light Water Reactors (LWRs) [2]. The CRUD which has generally micro-scaled pore geometry could have considered as porous layer and it was suggested that modification of heat transfer surface like CRUD can influence cooling rate during Loss-Of-Coolant Accident (LOCA) transient [3]. Therefore, role of porous layer will be more emphasized at core-safety analysis, because, recently strategy of nuclear-fuel operation gradually becomes higher burn-up and longer cycle.

As another aspect, study about film boiling has widely concerned due to its importance at core-coolability in LOCA, however, consideration of porous layer has relatively restricted because of difficulty of fabrication, excepting for horizontal surface. In this article, we briefly introduce experimental result of film boiling on porous layered surface during quenching. Laboratory-scaled quenching facility was applied [4] and porous layer was fabricated by Electro-Chemical Deposition (ECD) method at spherical brass test section.

2. Experiment

2.1 Test section and its surface characteristics

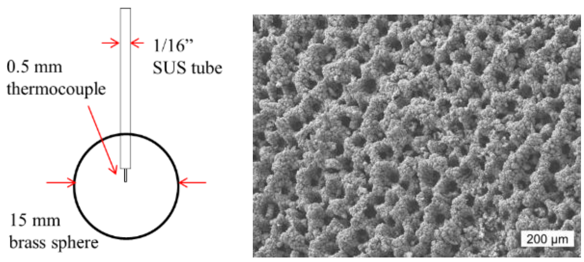

Fig. 1 (*Left*), Geometry of quenching test section, (*Right*), Characteristics of MPS

K-type thermocouple (diameter, 0.5 mm) was inserted into center of quenching test section, which is 15 mm diameter sphere, to evaluate temperature transient during rapidly cooling, and, 1/16 inch SUS tube supported the test section as well as protecting wire of thermocouple against high thermal condition (Fig. 1).

The ECD on metal substrate is based on reduction of metal ions in electrolyte (sulfuric acid and copper sulfate solution) under constant current density, and, deposition characteristics such as morphology and, thickness were determined by adjusted balance between reaction product (H_2 gas and Cu solid particle) [5]. We adopted ECD condition to optimal fabricate the porous-layer on brass sphere and evaluated surface morphology/wettability. Two test surfaces were selected; Bare Brass Surface (BBS) and Micro-Pores Surface (MPS). Through scanning electron microscope, averaged diameter of micro-pores and thickness of deposited layer at MPS were measured about 50 μm, 100 μm, respectively (Fig. 1). Mechanism of micro-hole formation is caused by generation of H_2 bubble with Cu deposition, simultaneously. This micro-pore consisted of numerous particles of which size is about 1-10 μm. Also, it was natural that the MPS has completely wetting characteristic (contact angle, θ~0°), contrasted by BBS (θ~60°) due to its inherent micro-pores morphology.

Before experiment, BBS and MPS were pre-treated by calcination to build pre-oxidation layer and to reinforce adhesion between deposited layer and brass substrate, respectively.

2.2 Experimental results

2.2.1 Temperature-time graph and boiling curve from quenching

Under atmospheric saturated distilled water, we conducted quenching experiment with high speed visualization to identify the effect of porous layer at film boiling. Apparent difference between BBS and MPS during quenching was, above all, overall cooling time t_{cool}. Contrasted by BBS (t_{cool}~60 s), MPS (t_{cool}~5 s) was extraordinarily cooled and it was caused by porous layer which have micro-pores geometry. The major reason of this could be explained as extinction of film boiling.

Representative feature at film boiling during quenching is linear temperature drop versus cooling time and it is due to thin vapor film exerting as insulating layer. Therefore, most of cooling time during quenching was spent by film boiling like the BBS. However, cooling rate of MPS (120 ℃/s) did not explain by general mechanism of film boiling such as conduction or radiation.

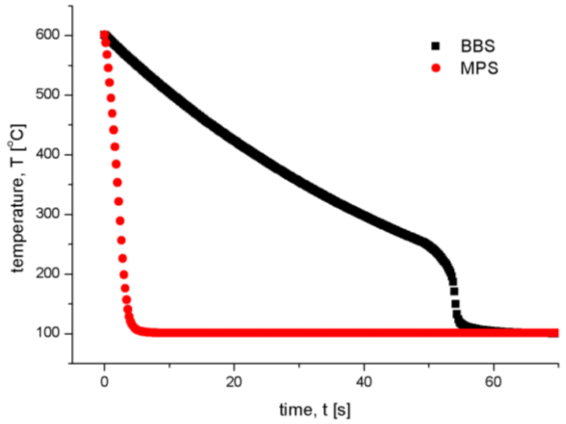

Fig. 2 Temperature-time graph during saturated distilled water quenching

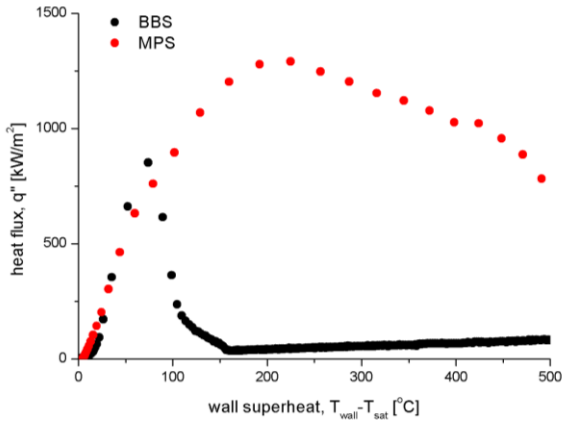

Fig. 3 Boiling curve obtained from temperature transient during quenching

Through boiling curve by lumped parameter method, film boiling characteristics on BBS was clearly identified; minimum film boiling temperature, T_{min}= 260 ℃, minimum heat flux, q''_{min}= 35 kW/m^2, and, heat transfer coefficient, h_{film}= 185 W/(m^{2}K) at T_{wall}= 420 ℃. Neglecting radiation effect (q''_{rad}/q''_{cond}<<1), h_{film} was governed by conduction across vapor film (Nu~1) and we could estimate vapor film thickness δ_{vapor} of BBS (200 μm at T_{wall}= 420 ℃). Contrasted by BBS, it was hard to consider as film boiling because of different order of magnitude at h_{film} (O~10^3 W/(m^{2}K)) or q'' (O~10^3 kW/m^2) in case of MPS. For satisfying h_{film} at MPS, δ_{vapor} must be below 50 μm which is quite small compared with the thickness of porous layer at MPS (100 μm).

2.2.2 Visualization

During film boiling of BBS, vapor film was totally wrapped around the brass sphere and was relatively stable (Fig. 4a). As T_{wall} was decreased, stable laminar vapor film became unstable and this suggested that vaporization during film boiling is too insufficient to sustain liquid-vapor interface (Fig. 4b). Contrasted by BBS, MPS had different phenomena; large vapor mushroom generated around brass sphere as soon as quenching starts (Fig. 4c,d). Diameter of mushroom was more than two times than sphere and through this, mechanism of vaporization was totally changed at the MPS, compared with the BBS.

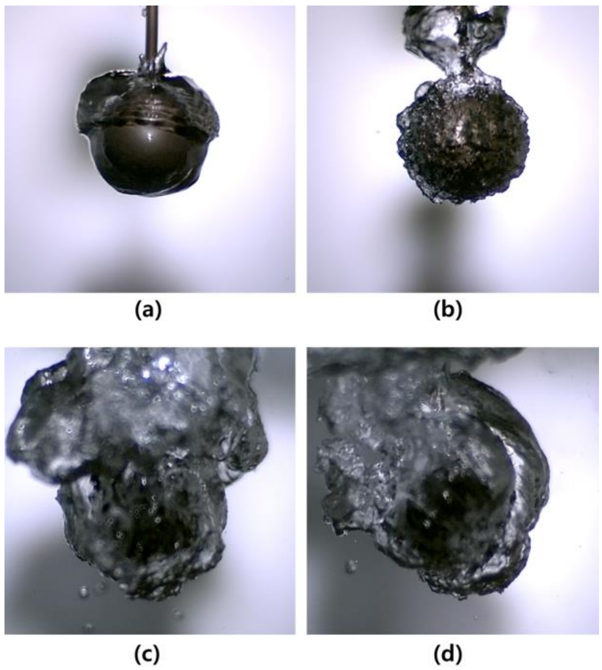

Fig. 4 High speed visualization during quenching, BBS under (a) T_{wall} ~420 ℃, (b) T_{wall} ~250 ℃ and MPS under (c) T_{wall} ~420 ℃, (d) T_{wall} ~250 ℃

The role of porous layer during film boiling was, firstly, absorption of vapor flow and effective vapor film thickness $\delta_{vapor,eff}$ could be decreased [6]. This will made chance to earlier collapse of vapor film by liquid-solid contact. Second was intermittent wetting during film boiling. Completely wetting of porous layered surface will significantly amplify amount of vaporization through intermittent wetting [4]. Also, even though we did not quantify noise characteristics, sputtering when quenching starts was identified at the MPS and this was based on vigorous vaporization when liquid contacts to overheated surface during film boiling.

Through our experiment, question is arose that is porous layer always an advantageous in cooling rate during quenching and what is the criteria about their thickness to improve the cooling rate? Based on this question, further analysis is planned; first is quantification of porous characteristics such as porosity, effective pore size at hierarchical nano-micro structures and their permeability fabricated by ECD recipe, and second is parametric analysis to identify effects of porous layer thickness and subcooled degree of coolant.

3. Conclusions

We observed that the existence of porous layer on heat transfer surface considerable affected the cooling rate ($t_{cool,MPS}/t_{cool,BBS}$~12) during quenching in a saturated distilled water, therefore, it is expected that porous layer like CURD may have the potential able to affect LOCA transient. During quenching, film boiling on porous layer was totally disappeared and it is expected that surface permeability able to flow of fluid (vapor or liquid) into porous layer plays major role of.

ACKNOWLEDGEMENT

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