Experimental Study of the Coolability of Debris Beds using a Non-heating methodology

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1. Introduction

When a severe accident proceeds to an ex-vessel scenario by the reactor pressure vessel (RPV) failure, the discharge of molten corium to the cavity filled with water, the droplet solidification and the debris bed settling occur in sequence (Fig. 1). The relocated debris beds may cause the molten core-concrete interaction (MCCI) [1-6]. In order to avoid the MCCI, it is important to evaluate the coolability of ex-vessel debris beds. The decay heat of the debris bed is removed by vaporization of water. Thus, the dryout heat flux (DHF) is defined as the maximum heat removal rate of debris beds [7-13]. It is important to investigate the influence of parameters (bed diameter, bed height, flooding condition, etc.) on the coolability of debris beds.

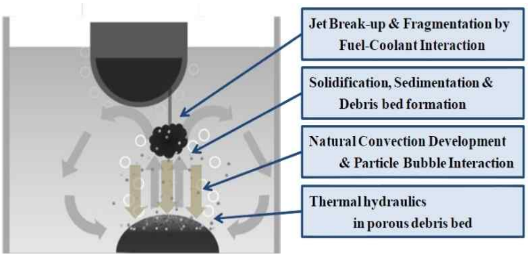

Fig. 1. A development process of corium debris bed in the flooded cavity pool [6].

In this study, the dryout heat flux (DHF) of debris beds was measured by mass transfer experimental methodology. The conventional copper electroplating system using $CuSO_4$-H_2SO_4, was extended to boiling heat transfer using the hydrogen generated at the cathode surface at a high potential. This non-heating method of DHF measurement simulates the uniform self-heating condition of debris beds. The copper and stainless steel cathode beds of 6 mm act as the volumetrically heated debris beds. The experimental apparatus was the polycarbonate pipe filled with the cathode beds and the aqueous solution of the sulfuric acid (H_2SO_4). For the bottom flooding condition, the heights of beds were from 20 to 60 mm.

2. Previous studies

The past works reported that the coolability of debris beds is affected by the bed diameter, bed height, porosity, flooding and coolant conditions, pressure, etc. Especially, the DHF depends on the bed diameter, bed height and flooding condition.

The dependence of the DHF on bed diameter and bed height was experimentally studied by Barleon *et al.* [8]. For top flooding condition, the bed diameter and bed height were varied 0.06 to 16 mm and 6 to 40 cm, respectively. The water or Freon-113 was used as the coolant. They reported the DHF increased with the bed diameter and decreased with the bed height irrespective of coolant type [14].

Hofmann [15] also conducted the DHF experiment for top flooding and bottom flooding condition. The beds were up to 0.5 m deep and consisted of 3 mm stainless steel balls. The coolant was the water. For top flooding condition, the onset of dryout occurred near the bottom of the bed. For bottom flooding condition with permeable base, the dryout started near the top of the bed, and the DHF was more than twice as high as that from top flooding condition. The similar results for the flooding condition were reported by Atkhen and Berthoud [3], Rashid *et al.* [11], Squarer and Peoples [18], and Kulkarni *et al.* [19].

Afterward, Hofmann [16] confirmed the influence of the bed diameter and height on the DHF for the top flooding condition. The uniform beds consisted of stainless steel balls of 1 and 3 mm in diameter up to 100 cm height. They mentioned that the DHF decreased with increasing bed height. Dhir and Catton [17] also reported the similar result. Yamano *et al.* [1], Kim *et al.* [6], Bang and Kim [12], Hofmann [16], Squarer and Peoples [18] also confirmed the dryout heat density was improved by the bed diameter.

Although there have been considerable studies on the DHF of the debris beds either experimentally or theoretically, the range of parameters (bed diameter, bed height, porosity, etc.) was scattered due to uncertainty about the formation and settling of debris bed. Thus, it is difficult to compare the results of the existing studies.

3. Experiments

3.1 Analogy concept with the electroplating system

Heat and mass transfer systems are analogous, as the governing equations and parameters are of the same form mathematically [20, 21]. The experimental method using a copper sulfate-sulfuric acid ($CuSO_4$-H_2SO_4) electroplating system based on the analogy concept is well-established [22-28].

The copper sulfate-sulfuric acid ($CuSO_4$-H_2SO_4) electroplating system was generally used for analogy experiments for simulating single phase heat transfer system. This system is composed of the copper anode and the copper cathode submerged in an aqueous solution ($CuSO_4$-H_2SO_4).

3.2 Extended mass transfer experimental methodology

When the applied potential between cathode and anode increases, the current increases initially and then reaches a plateau. The current at the plateau is called as the limiting current. When the potential increases further beyond the limiting current region, the hydrogen ions reduce and the current increases again. It causes the evolution of hydrogen gas at the cathode.

The basic idea of this study is that the vaporization can be simulated by the hydrogen gas generated at the cathode surface. The hydrogen film covering the cathode surface can be formed and the DHF condition in the heat transfer can be simulated [29]. When the electric potential is applied between the cathodes and anode, all the cathode beds of copper and stainless steel have the same potential difference, which means that a uniformly heating condition can be simulated.

Based on the assumption as mentioned above, the authors hypothesized that hydraulic behavior of gas over the arbitrary solid surface will be similar under the identical gaseous volume generation rate (η). Thus, the DHF can be calculated with Eq. (1) introducing the gas generation rate (η).

$$q_{DHF} = \eta h_{lg} \rho_g \tag{1}$$

The hydrogen generation rate (η) is determined by the electric current, charges for hydrogen reduction and Avogadro number (Eq. (2)).

$$\eta = V_m \left(\frac{T}{273.15} \right) \left(\frac{I}{neN_A} \right) \tag{2}$$

3.3 Experimental apparatus

Figure 2 presents the electric circuit of the experimental apparatus consisted of a power supply, a data acquisition system, a polycarbonate pipe containing the cathode beds and anode. In order to minimize the cupric ion reaching the cathode, the polycarbonate pipe of test section is divided to the cathode part and the anode part. The inner diameter and length of cathode part pipe is 46 mm and a length 815 mm. The diameter of copper and stainless steel beds is 6 mm. The height of beds is ranged from 20 to 60 mm. The test section is filled with the sulfuric acid solution (H_2SO_4) of 1.5 M. For the bottom flooding condition, the top and bottom of bed were open and the copper cathode beds were rested on a permeable support grid. The bed porosities (ε) of the copper beds were 0.374, 0.404 and 0.415 for the heights of 20, 40 and 60 mm, respectively. The copper anode of 35 mm × 35 mm × 50 mm was placed at the anode part to supply the electric charges and isolate the cupric ions generated at the anode. The power supply was used to apply current and data acquisition system was employed to record the experimental results. As the polycarbonate pipe was transparency, we can observe the behaviors of hydrogen vapor.

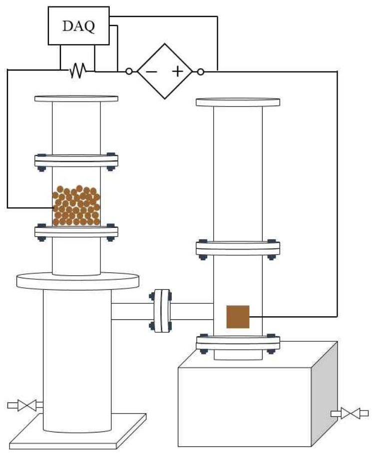

Fig. 2. The electric circuit of experimental apparatus.

4. Results and discussion

Figure 3 shows the measured currents depending on the applied potentials. The electric potential and the current of this study correspond to the temperature difference and the heat flux in the heat transfer system, respectively. For a step application of the electrical potential, a high current is measured initially and then it reduces to a certain value with the stabilization of the convection phenomena. After the stabilization, a step increase of the electric potential is made until a sudden drops of the current were observed. In Fig. 3, at the potential of 90 V and the current of 50 A, the sudden drops of the current were observed. For high power, the pressure developed by the generated hydrogen gas retards the inflow of the sulfuric acid (H_2SO_4) solution into the copper cathode beds. The copper beds become dry and the flow of the electric current is blocked. It is similar to the dryout mechanism of heat transfer system.

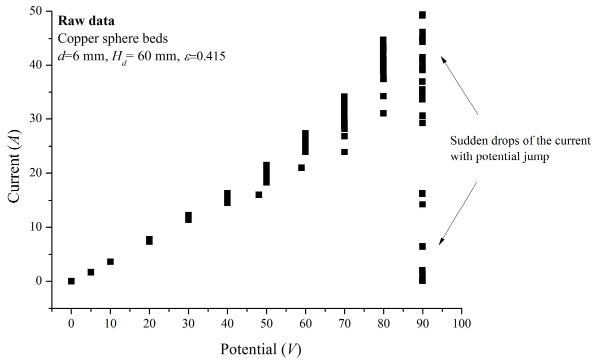

Fig. 3. Potential and current values reaching the dryout.

Figure 4 indicates the measured current and potential at the stabilized conditions. Almost linear increase of current with the potential was observed to reach the dryout condition. As a result, the calculated DHF by using Eq. (1) and (2) was 7.03 kW/m^2. The results of the existing studies on the DHF for the bottom flooding condition are summarized in Table Ⅰ. The result of this study is about 300 times smaller than those of existing heat transfer studies. This discrepancy seems to be due to the differences in the physical parameters influencing the boiling mechanism. A plausible explanation for the discrepancy of the results is that the bottom flooding condition wasn't fully simulated because the captured hydrogen bubbles were observed at the underneath of the permeable support grid. As the captured bubbles obstructed the inflow of the sulfuric acid solution, the dryout condition was reached early. In addition, it was possible that the electric resistance of test section had increased due to the long distance between cathodes and anode. In further studies, these are to be improved through some parametric corrections and design upgrade of test apparatus.

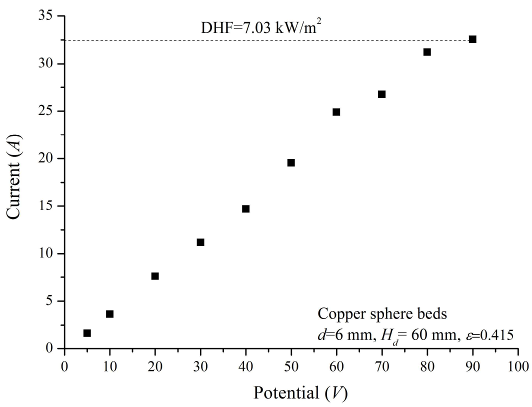

Fig. 4. Average potential and current values at equilibrium state reaching the dryout for the copper beds of H_d=60 mm.

Table Ⅰ: The DHF of the existing studies.

Authors	***d* (mm)**	***H$_d$* (m)**	***ε***	**DHF (kW/m^2)**
Hofmann [15]	3	0.485	0.405	2,200
Bang and Kim [12]	3.2, 4.8	0.3	0.37, 0.38	900-1,200
Barleon *et al.* [8]	2	0.2	0.373	630
Cha and Chung [30]	1.5-4	0.11	-	900-1,800
Hu and Theofanous [7]	7-9	1.02	-	612

Figure 5 shows the DHF according to the bed height (H_d) of copper and stainless steel beds. The bed height was varied from 20 to 60 mm. The experiments were performed for the bottom flooding condition. The DHF increases with the bed height regardless of the cathode materials. This trend is similar to those of existing studies [3, 8, 15-18].

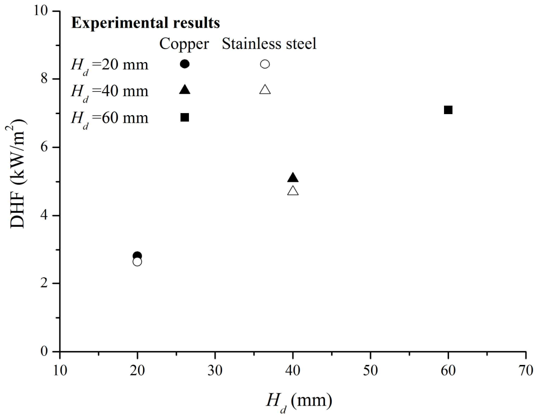

Fig. 5. Dryout heat flux according to the bed height (H_d) of copper and stainless steel beds.

5. Conclusions

The dryout heat flux (DHF) was measured by the mass transfer system extended the conventional copper-sulfate electroplating system, which is composed of the sulfuric acid solution and the copper electrodes. The basic idea of the non-heating methodology is to use the hydrogen bubble, generated at the cathode surface at a high potential difference. Thus, this non-heating method of DHF measurement simulates the uniform self-heating condition of debris beds.

The DHF can be directly calculated by the measured electric current from the present work. The DHF was improved by the increase of the bed height regardless of the cathode materials. The tendency for the DHF depending on the bed height is similar to that of existing studies. However, the measured DHF values had large discrepancy with those of the existing heat transfer studies. The discrepancy is natural due to the physical parameters influencing the boiling mechanism. Also, the obstruction of inflowing the sulfuric acid solution occurred as the hydrogen bubbles were captured at the underneath of the permeable support grid. Thus, some parametric corrections are needed based upon the existing DHF models and literature. The design of the experimental apparatus must be upgraded to eliminate the factors increasing the uncertainty of experimental data.

This study presents the potential of the non-heating experimental method extending the existing analogy mass transfer methodology using the copper electroplating system. Obviously, further studies such as the influence of the flooding condition and system pressure must be performed to approach the heat transfer system.

ACKNOWLEDGEMENT

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