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Simulation of Natural Convection in the Oxide Layer of Three-Layer Corium Pool in an IVR

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1. Introduction

The IVR-ERVC (IVR-ERVC: In-Vessel Retention-External Reactor Vessel Cooling) is a effective strategy for maintaining the reactor vessel integrity during a severe accident. In a severe accident, the fuels melt and are assumed to stratify as a two-layer (upper light metal layer and the lower oxide layer) or a three-layer (upper light metal layer, middle oxide layer and lower heavy metal layer) by the density difference. Between two-layer and three-layer phenomena, the natural convective flows inside the oxide pool are different due to geometrical difference. Especially for the three-layer configuration, the light metal layer becomes thinner, resulting in the intensification of focusing effect. It means the molten pool configuration is important for the precise evaluation of heat load and integrity of reactor vessel. Generally, a lot of researches assumed a two-layer configuration. However, few studies were performed for a three-layer configuration yet. This study is focusing on the oxide pool in a three-layer configuration.

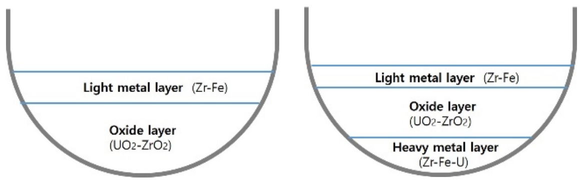
This paper describes the three-layer phenomena and preliminary plan to simulate the oxide layer experimentally. We will perform the mass transfer experiments using a copper sulfate–sulfuric acid ($CuSO_4$–H_2SO_4) electroplating system based on the heat and mass transfer analogy concept. By performing the mass transfer experiments, we can achieve the high buoyancy condition with small facilities. The test facility is semicircular whose bottom is chopped, simulating the oxide pool above the heavy metal layer in a three-layer configuration. (MassTER-OP2(HML): Mass Transfer Experimental Rig for a 2D Oxide Pool above Heavy Metal layer) We will measure the heat flux at the top plate, side wall and bottom plate, and compare these results with those for a two-layer pool.

2. Theoretical Background

2.1 Phenomena

In a severe accident, the molten core relocate to the lower vessel plenum. In general, it is assumed that the metallic materials, such as Zr and Fe, and the oxidic materials, such as ZrO_2 and UO_2, may form and be stratified as two-layer by the density difference, shown as Fig. 1(a). However, MASCA experiment [1] reported that when the Zr is sufficiently non-oxidized, the U migrates to the metallic layer, increasing the density of metallic layer. Then, it leads to the layer inversion and the three-layer formation with an additional heavy metal layer at the bottom, shown as Fig. 1(b). The top layer contains the Zr and Fe from the original present after subtracting the portion which combined into the U. The middle oxide layer is consist of the UO_2, ZrO_2 and most of the fission products. The bottom heavy metal layer contains the Zr, Fe and U with some metallic fission products. The thickness of the light metal layer decreases due to the formation of heavy metal layer, causing the focusing effect in the metallic layer.

In a three-layer configuration, the oxide layer is chopped-semicircular shaped, and the decay heat is transferred to the top plate, side wall and bottom plate as shown Fig. 2.



(a) two-layer (b) three-layer

Figure 1. Stratified molten pool configuration

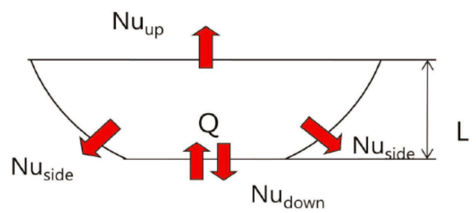


Figure 2. Heat transfer in the oxide layer of three-layer of corium pool [2]

2.2 Previous studies

A lot of existing studies performed heat transfer experiments for the oxide layer in a two-layer system. However, there were few researches on the three-layer corium pool. Several analysis researches [2, 3] reported the material composition and the height of each three layer using the code calculation, and just one experimental research (SIMECO) [4] simulated the three-layer system.

2.2.1 Three-layer experiments

SIMECO experiments used paraffin oil, water and chlorobenzene as simulants for the stratification of three-layer. These simulants were determined by density, specific heat coefficient, miscibility and toxicity. The height of upper layer (Paraffin oil), middle layer (water) and lower layer (Chlorobenzene) were 5 cm, 8 cm and 4 cm, respectively. The 20 cm heater is located on the 4cm elevation, supplying the heat to the entire middle layer and part of upper layer. The Ra'_H was 6.01×10^{12} and 7.82×10^{12}. They observed the heat flux ratio of upwards to downwards and the angular heat distribution to the vessel. The heat flux ratio was higher for three-layer system than for two-layer system. And the angular heat flux increased along the angle, peaked in the vicinity of 57 degree, which is about intermediate section of middle layer, and decreased consistently. This couldn't explain the focusing effect in the metallic layer.

This SIMECO test was not complete enough to describe the three-layer phenomena. First, the three-layer test is a minor case among the SIMECO tests. So, the results analysis and explanation were insufficient. Second, there is no reason to determine the height of each three layer. Finally, the results of SIMECO two-layer test, which was performed in same conditions with three-layer tests except for subtracting the bottom layer (chlorobenzene), were significantly different from other existing two-layer results.

2.2.2 Two-layer experiments

MassTER-OP2 test [5] simulated the oxide pool in a two-layer configuration. Based on the analogy concept between heat and mass transfer, they performed the mass transfer experiments in a two-dimensional semi-circular facility. The angular heat flux increases with the angle and has a maximum value at the 90°. The working fluid is copper sulfate – sulfuric acid fluid. The Ra'_H was range of 10^{13} -10^{14}.

SIGMA CP test [6] investigated the natural convection heat transfer from oxide layer in a two-layer configuration. They performed in a two-dimensional semi-circular pool and used air and water as working fluids. The Ra'_H was 5.71×10^{6} and 7.04×10^{11} respectively. The angular heat flux increases with angle of the lower plenum, has a peak between 80° and 90° and decreases slightly up to 90°. They developed the heat transfer correlations as below:

$$Nu_{up} = 0.31(Ra'_H Pr^{-0.36})^{0.245} \quad (1)$$

$$Nu_{dn} = 0.219(Ra'_H Pr^{-0.215})^{0.235} \quad (2)$$

BALI experiment [7] simulated the oxide pool of two-layer corium using a two-dimensional semi-circular facility with Ra'_H of 10^{15} – 10^{17}. The working fluid was water adding cellulose. The angular heat flux increases up to 90° when the pool angle increases. The developed heat transfer correlations were as below:

$$Nu_{up} = 0.383\ Ra'^{0.233}_H \quad (3)$$

$$Nu_{dn} = 0.116\ Ra'^{0.25}_H \quad (4)$$

ACOPO experiment [8] was performed in the 3D hemispherical pool, simulating the oxide pool in a two-layer configuration. The angular heat flux increases up to 90° with the angle of lower vessel plenum. The working fluid was water. They developed the correlations with the Ra'_H range of 1×10^{12} and 2×10^{16}.

$$Nu_{up} = 1.95\ Ra'^{\,0.18} \quad (5)$$

$$Nu_{dn} = 0.3\ Ra'^{\,0.22} \quad (6)$$

2.3 Definition of Ra'_H

Since the oxide layer emit the decay heat, we should establish the internal heat generation. Thus, the modified Rayleigh number (Ra'_H) is used intead of conventional Rayleigh number (Ra_H), allowing to describe the natural convection heat transfer pheneomena involving volumetric heat generation. The Ra'_H is expressed by

$$Ra'_H = Ra_H \times Da\ , \quad (7)$$

$$\text{Damköhler number } (Da) = \frac{q'''H^2}{k\Delta T} \text{ and} \quad (8)$$

$$Ra'_H = \frac{g\beta\Delta TH^3}{\alpha\nu} \times \frac{q'''H^2}{k\Delta T} = \frac{g\beta q'''H^5}{\alpha\nu k} \quad (9)$$

3. Experiments

3.1 Methodology

This study will perform mass transfer tests using the electroplating system based on analogy between heat and mass transfer. The *Sh* and *Sc* of mass transfer analogy with *Nu* and *Pr* of heat transfer, respectively.

A mass transfer experiment using the electroplating system was performed first by Levich [9]. After that, Selman [10] organized mass transfer correlations in different conditions. Chung et al [11] performed mass transfer experiments to explain the methodology in detail. Since it is difficult to know the concentration of copper ion near the cathode surface, we will use a limiting current technique. When the potential between electrodes increases continuously, the current increases up to the plateau section, which is steady in spite of the potential increase. The current in plateau section is the limiting current. In the limiting current, the concentration of copper ion on the cathode surface is considered almost zero. Therefore, mass transfer coefficient (h_m) is defined as:

$$h_m = \frac{(1-t_{Cu^{2+}})I_{\lim}}{nFC_b} \quad (10)$$

Because buoyancy towards bottom of the facility is formed in heat transfer, cold wall could be simulated as anode in mass transfer. However, the limiting current is not measured in anode. [12] Therefore we will perform the tests using the facility inverted against the gravity direction and can simulate the cathode as cold wall.

3.2 Experimental facility

Figure 3 indicates the experimental facility of MassTER-OP2(HML): Mass Transfer Experimental Rig for a 2D Oxide Pool above Heavy Metal layer. The facility is two-dimensional semi-circular whose bottom is chopped. The radius of 10 cm and width 4 cm are same with previous MassTER-OP2 facility [5]. The height of 4 cm was determined by the existing analysis results [2]. The cathode copper plates were attached on the inner wall of the top, curved side and bottom. In order to measure local current, half of the copper is divided by 4 pieces on the top, 7 pieces on the curved side and 5 pieces on the bottom. The trapezium anode copper is fixed on the both flat side wall, simulating the internal heat source. The facility is filled with copper sulfate–sulfuric acid ($CuSO_4$–H_2SO_4) fluid. Figure 4 shows the system circuit. The multi-meters are connected with cathode coppers in parallel. The Ra'_H is expected about 10^{13}. The Pr is 2,014.
Table1 presents the test matrix.

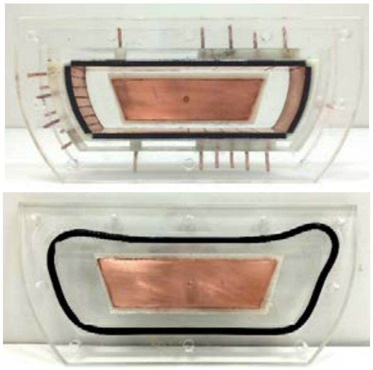


Figure 3. Experimental facility

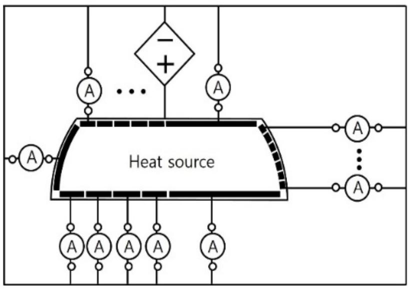


Figure 4. Experimental circuit

Table 1. Test matrix for experiments

Boundary condition			*Pr*
Top	**Side**	**Bottom**	
Cooling	Cooling	Cooling	2,014
		Insulated	
Insulated		Cooling	
		Insulated	

3.3 Expected results

Figure 5 shows the expected flow patterns in the oxide pool for a two-layer and three-layer configuration respectively. In a three-layer configuration, the natural convective flows run down along the curved surface and bottom plate. At the center of the bottom plate, flows merge and rise upward. Underneath the top plate, the rising flows disperse towards the edge. These three-layer flows may be weaker than two-layer flows. Especially, the weak rising flows may cause the decrease of heat flux at the top plate comparing with the two-layer results. At the side curvature, the angular heat flux will increase with the angle. But, unlike the two-layer results, the enhancement may exist at the lower angle because the downward flows along the cured surface could collide the bottom plate.

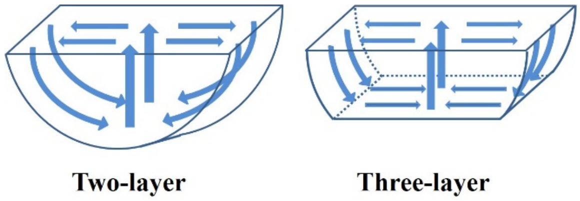


Figure 5. Flow patterns in the oxide pool

4. Conclusions

In a three-layer configuration, the upper light metal layer becomes thinner, increasing the focusing effect. Thus, it is important to evaluate the heat flux from the oxide pool to the upper metallic layer. However, there is few heat transfer studies for a three-layer configuration.

This paper is to discuss and to make a plan for the heat transfer experiments of oxide pool in a three- layer system. We will perform the mass transfer experiments based on the heat and mass transfer analogy concept. The test results will be analyzed phenomenologically and compared with two-layer results.

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