Natural Convection Heat Transfer of the Oxide Layer Varying the Aspect Ratios for a Three-Layer Configuration

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1. Introduction

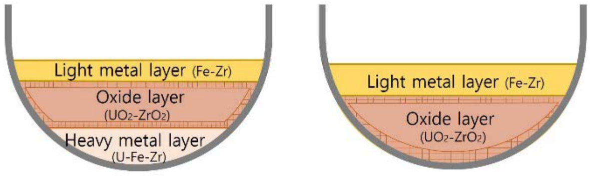
The IVR-ERVC (In-Vessel Retention-External Reactor Vessel Cooling) retains the melted fuels inside the reactor vessel and cools them by flooding the cavity. This strategy is effective to maintain the reactor vessel integrity and prevent the release of radioactive materials into the containment environment. [1] In a severe accident, the molten fuels relocate the lower vessel and are stratified into two-layer (upper metal layer and lower heavy oxide layer) or three-layer (upper light metal layer, middle oxide layer and lower heavy metal layer) by density differences. In a three-layer configuration, the heat focusing to the vessel is intensified as the thickness of upper metal layer is reduced. However, there are only a few researches on the three-layer configuration.

This study simulated the natural convection heat transfer of the oxide layer in a three-layer configuration varying the aspect ratios. Based upon analogy concept, mass transfer experiments were carried out using copper sulfate–sulfuric acid ($CuSO_4$–H_2SO_4) electroplating system. The high buoyancy was achieved using small facilities by employing the mass transfer tests. The Ra'_H ranged from 10^{11} to 10^{13}. The test facilities were semicircular with chopped bottom, whose aspect ratios are 0.28, 0.56 and 0.78 respectively. (MassTER-OP2(HML): Mass Transfer Experimental Rig for a 2D Oxide Pool above Heavy Metal layer) The upward heat ratios and local heat transfers were measured and compared for different aspect ratios. Also, the flow patterns were analyzed phenomenologically.

2. Theoretical Background

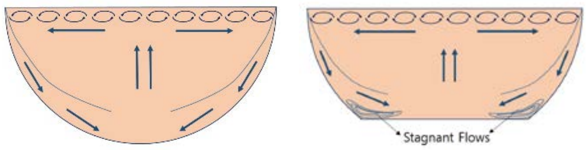
2.1 Phenomena

In general, the molten core is assumed to be stratified into two-layer as shown in Fig. 1(a). Upper layer contains metallic materials such as Zr and Fe, and the lower layer contains oxidized materials such as UO_2 and ZrO_2. However, MASCA research [2] discovered that when Zr is oxidized insufficiently, U migrates the upper metal layer and increase the metal layer density, resulting in layer conversion with heavy metal layer as shown in Fig. 1(b). The top light metal layer consists of Zr and Fe. The middle oxide layer consists of UO_2, ZrO_2 and most of the fission products. The bottom heavy metal layer consists of U, Fe, Zr and some metallic fission products. In a three-layer configuration, the focusing effect is intensified due to heavy metal layer formation reducing the light metal layer thickness. [3]



(a) two-layer (b) three-layer
Figure 1. Stratified molten pool configuration.

Figure 2(a) shows the flow patterns in the two-layer configuration. The natural convective flows run down along the curved surface, merge at the bottom and move upward. And, they dispherse towards the edge of top plate. There are also natural convective flows underneath the top plate. [4] The similar flow patterns are expected for the three-layer configuration as shown in Fig. 2(b).



(a) two-layer (b) three-layer
Figure 2. Flow patterns.

2.2 Previous studies

2.2.1 Two-layer experiments

BALI experiment [4] simulated the oxide layer for the two-layer configuration using a 2-D semi-circular test rig. The facility scale was 1:1 with prototypic French PWR reactor. The working fluids were cellulose added water. The angular heat flux increased up to 90° and its profiles were influenced by the top boundary condition. The correlations for Nu_{up} and Nu_{dn} were developed in the Ra'_H of 10^{15}–10^{17}.

$$Nu_{up} = 0.383\, Ra'^{0.233}_H \text{ and} \qquad (1)$$

$$Nu_{dn} = 0.116\, Ra'^{0.25}_H. \qquad (2)$$

SIGMA CP test [5] performed natural convection heat transfer of the oxide pool in a two-layer configuration using a 2-D semi-circular facility. They used air and water as working fluids. The Ra'_H ranged from 10^6 to 10^{11}. The angular heat flux increased with angle. It peaked between 80° and 90° and decreased slightly up to 90°. At the top plate, the local heat flux was scattered showing no obvious relationship. They developed the correlations for Nu_{up} and Nu_{dn}.

$$Nu_{up} = 0.31(Ra'_H Pr^{-0.36})^{0.245} \text{ and} \tag{3}$$

$$Nu_{dn} = 0.219(Ra'_H Pr^{-0.215})^{0.235}. \tag{4}$$

MassTER-OP2 and MassTER-OP3 tests [6] simulated the natural convection heat transfer of oxide pool in a two-layer configuration in a 2-D and 3-D geometry. They used the 2-D semi-circular and 3-D hemi-spherical facilities with three different heights. The Ra'_H ranged from 10^{12} to 10^{15}. The mass transfer experiments were performed using the copper sulfate–sulfuric acid solution as working fluids. The angular Nu increased up to 90°. The trend was not affected by top cooling condition. The local Nu at the top plate decreased from center to edge. They developed the corrleations which cover both 2-D and 3-D results.

$$Nu_{up}=1.046Ra'_H{}^{0.211} \text{ and} \tag{5}$$

$$Nu_{dn}=0.27Ra'_H{}^{0.209}. \tag{6}$$

2.2.2 Three-layer experiments

SIMECO research [7] simulated the stratified three layers using paraffin oil (top layer), water (middle layer) and chlorobenzene (bottom layer) in the 2-D geometry. The heights of top layer, middle layer and bottom layer were 5 cm, 18 cm and 4 cm respectively. On the 4 cm elevation, the 20 cm long heater was located, keeping the bottom layer unheated. The Ra'_H ranged from 6.01×10^{12} to 7.82×10^{12}. They also simulated the two-layer configuration in the same condition with the three-layer configuration except for the bottom layer. The heat flux ratios of upwards to downwards were higher for three-layer configuration than two-layer configuration. The angular heat fluxes increased with the angle and peaked at the middle of the oxide layer: 64 degree for three-layer test and 57 degrees for two-layer test. This result is different with other studies on two-layer configuration that the peak appeared at uppermost section of oxide layer.

The SIMECO tests did not focus on the oxide layer. The measurements were obtained for certain section. The heights of three layers were determined arbitrarily. The local results in two-layer configuration were inconsistent with other existing results.

2.3 Definition of Ra'_H

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

$$Ra'_H = Ra_H \times Da \ , \tag{7}$$

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

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

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 [8]. After that, Selman [9] organized mass transfer correlations in different conditions. Chung et al [10] 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:

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

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. [11] Therefore we will perform the tests using the facility inverted against the gravity direction and can simulate the cathode as cold wall.

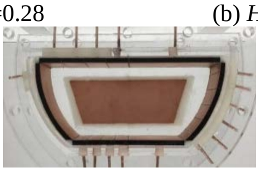
3.2 Experimental facility

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 2-D semi-circular with chopped bottom. The radius of 10 cm and width 4 cm are same with previous MassTER-OP2 facility. [6] The heights are varied to 0.028 m, 0.056 m and 0.78 m which correspond to aspect ratio of 0.28, 0.56 and 0.78. The height of 0.056 m was determined by code calculation result in the existing research. [3] The other heights were determined as intermediate values between 0 m and 0.056 m, and between 0.056 m and 0.1 m. The cathode copper plates were attached on the inner wall of the top, curved side and bottom. The halves of copper are single electrodes and the other halves are piecewise electrodes in order to measure local current. The trapezium anode copper is attached 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.

(a) *H*/*R*=0.28

(b) *H*/*R*=0.56



(c) *H*/*R*=0.78

Figure 3. Experimental facility.

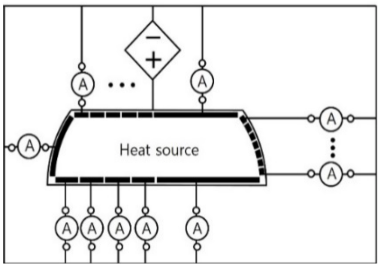


Figure 4. Experimental circuit.

Table 1. Test matrix for experiments.

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

4. Results and discussion

4.1 Upward heat ratio

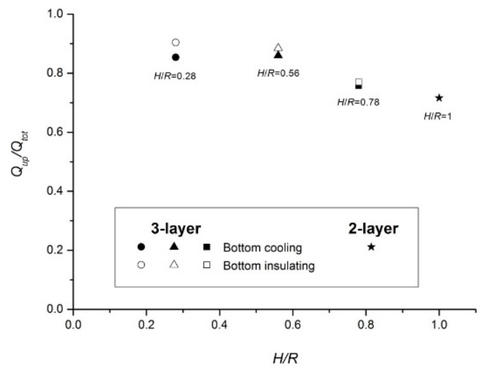


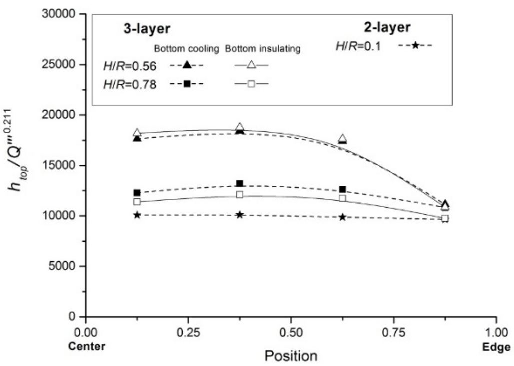
Figure 5. Upward heat ratio according to aspect ratios.

Figure 5 compares the ratios of upward heat to total heat (Q_{up}/Q_{tot}) for different aspect ratios in two different bottom conditions. The upward heat ratios increased as the aspect ratios decreased. It is because the rising plume towards the top plate is hotter as cooling side wall is short for small aspect ratio. The three-layer results in all cases are higher than the two-layer result which means the three-layer configuration is worse than two-layer configuration due to intensification of focusing effect.

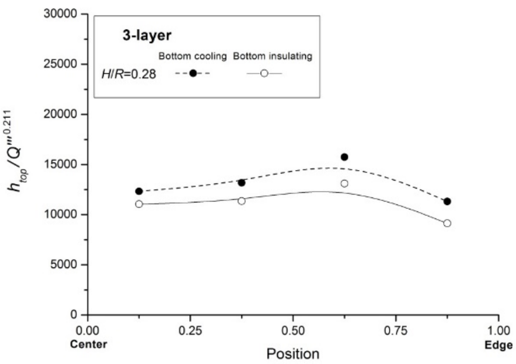
4.2 Local heat transfer

The decay heat was simulated differently in each test as it was determined by achieving the limiting current. So, the test results were normalized using MassTER-OP correlation. In MassTER-OP correlation, the *Nu* for the top plate is proportional to the Ra'_H to the power of 0.211, i.e. Q''' to the power of 0.211. The measured results were divided by Q''' to the power of 0.211. For the side wall, the measured results were normalized in the same way.

4.2.1. Top plate



(a) *H*/*R*=0.56, *H*/*R*=0.78 and *H*/*R*=0.1



(b) *H*/*R*=0.28

Figure 6. Local heat transfer at the top plate.

Figure 6 shows the local heat transfer at the top late. In Fig. 6(a), the results decreased from center to edge. The slope was steeper for small aspect ratio as the weak buoyancy forms causing weak rising plume. On the other hand, the results for the aspect ratio of 0.28 increased until 0.625 position and decreased as shown in Fig. 6(b).

It is because the multi cell flows are expected for the flat geometry as shown in Fig. 7. The bottom cooling condition didn't affect the result trends.

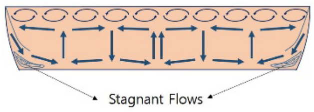
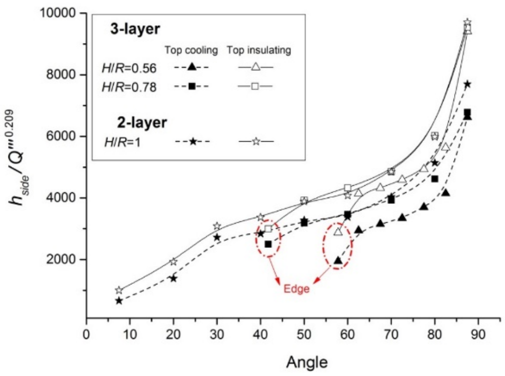
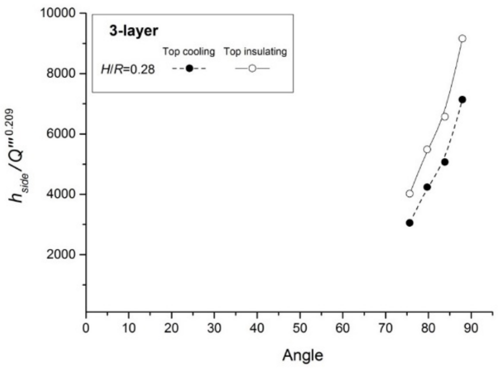


Figure 7. Expected flow patterns for small aspect ratio.

4.2.2. Side wall



(a) *H*/*R*=0.56, *H*/*R*=0.78 and *H*/*R*=0.1



(b) *H*/*R*=0.28

Figure 8. Local heat transfer at the side wall.

Figure 8 indicates the local heat transfer at the side wall. In all cases, the results decreased when the angle decreased as the boundary layer developed along the side wall. For the three-layer configuration, the results dropped sharply near the edge due to stagnant flow around the edge. The trends of measured results were not influenced by the top cooling condition.

5. Conclusions

In this study, the natural convection heat transfer of oxide layer were investigated for the three-layer configuration. We varied the aspect ratios and carried out phenomenological analyses. The mass transfer experiments were performed based upon analogy concept between heat and mass transfer. The upward heat ratios increased for small aspect ratio resulting the higher heat focusing to the vessel. And those are higher for three-layer configuration than for two-layer configuration which means the three-layer configuration were severer than two-layer configuration. The local heat transfer at the top plate decreased from center to edge except for very small aspect ratio. It is because the multi cell flows are expected in the flat geometry. The local heat transfer at the side wall decreased with the decreased angle in all cases. For the three-layer configuration, the sharp drops appeared around the edge due to stagnant flows.

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