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Investigation of Focusing Effect according to the Cooling Condition and Height of the Metallic layer in a Severe Accident

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1. Introduction

The Fukushima nuclear power plant accident has led to renewed research interests in severe accidents of nuclear power plants. In-Vessel Retention (IVR) of core melt is one of key severe accident management strategies adopted in nuclear power plant design.

The metallic layer is heated from below by the radioactive decay heat generated at the oxide pool, and is cooled from above and side walls. During the IVR process, reactor vessel may be cooled externally (ERVC) and the heat fluxes to the side wall increase with larger temperature difference than above. This "Focusing effect" is varied by cooling condition of upper boundary and height of the metallic layer [1].

This study investigated the focusing effect depending on the cooling condition of upper boundary and height experimentally and numerically. The Rayleigh number and aspect ratio (*H/R*) ranged from 8.49×10^7 to 5.43×10^9 and 0.135 to 0.541 respectively. Also, the conditions of the top plate and the side wall are considered: (a) top plate cooling, side wall adiabatic, (b) top plate adiabatic, side wall cooling, (c) both walls cooling. The heat transfer experiments were replaced by mass transfer experiments based on heat and mass transfer analogy concept. A sulfuric acid–copper sulfate (H_2SO_4–$CuSO_4$) electroplating system was adopted as the mass transfer system. Numerical analysis using the commercial CFD program FLUENT 6.3 were carried out with the same material properties and cooling conditions to examine the variation of the cell.

2. Previous studies

The molten pool may be formed in a severe accident at the lower head of reactor vessel and stratified into two layers by the density difference: an upper metallic layer (mostly consisting of Fe and Zr) and a lower oxide pool (largely consisting of UO_2 and ZrO_2) [2]. The metallic layer receives heat from the oxide pool and undergoes Rayleigh-Benard convection together with heat transfer to the vessel wall, subject to a highly elevated heat flux; see Fig. 1. This "Focusing effect" can be counteracted by two mecahnism: cooling condition of upper boundary and aspect ratio (*H/R*), owing to the small aspect ratio and hotter condition of upper boundary at which this focusing effect begins to become important [1].

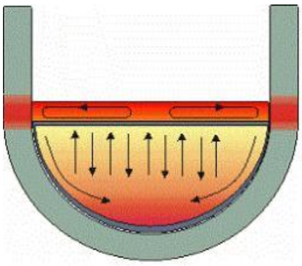


Fig. 1 Distribution of relocated molten core material.

Liu and Theofanous [3] investigated the correlations concerning heat transfers at the top/bottom and side boundaries. The experimental apparatus, called the MELAD (Metal Layer Demonstration), consists of a rectangular water box 50cm long, 10cm wide, and 10cm in height. The top and one of the sides are cooled to desired temperatures; the other side is thermally insulated, and the bottom is heated by direct electrical current using a steel foil. The front and back faces of the apparatus are insulated to create a 2D behavior. They explained that the test results show very good agreements with Globe-Dropkin correlation and that the local formulation of the Globe-Dropkin correlation combined with the Chu-Churchill correlation for the side wall are quite adequate.

Massimo Corcione [4] carried out a numerical study on the 2-D horizontal rectangular enclosures heated from below and cooled from above. The numerical study was performed on a variety of thermal boundary conditions at the side walls. The Rayleigh number and aspect ratio (H/R) ranged from 10^3 to 10^6 and 0.66 to 8 respectively. Massimo Corcione reported that the number of cells for the flow field increases as the aspect ratio decreases. In case of cooling condition at side walls, the heat transfer was improved than adiabatic condition of side walls due to direct heat exchange.

3. Experimental and numerical analyses

3.1 Experimental apparatus

Figure 2 shows the system circuit. The apparatus is a cylindrical tank made of acryl, of which the bottom is the copper cathode and the top and side are copper anodes. The radius of tank is 0.074m, and the height of side wall is varied. The lower plate simulates the hot wall and the top plate and side wall simulate cold upper and side wall in the heat transfer system.

The test matrix shown in Table I. The Rayleigh number and aspect ratio (*H/R*) ranged from 8.49×10^7 to 5.43×10^9 and 0.135 to 0.541, respectively.

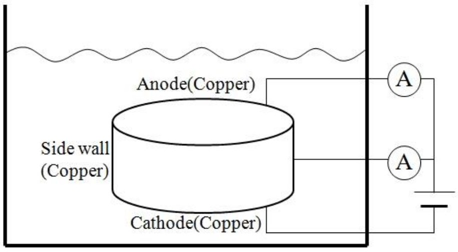


Fig. 2. The experimental apparatus.

Table I: Test matrix.

Pr	***R*(m)**	***H*(m)**	***H/R***	***Ra_H***	***Cooling condition***
2,014	0.074	0.01	0.135	8.49×10^7	Top cooling only, Side cooling only, Top+Side cooling
		0.015	0.202	2.87×10^8	
		0.02	0.270	6.79×10^8	
		0.04	0.540	5.43×10^9	

3.2 Experimental Methodology

In order to achieve high Rayleigh number, mass transfer experiments were performed replacing heat transfer experiments based upon analogy between heat and mass transfer [5]. A sulfuric acid-copper sulfate (H_2SO_4-$CuSO_4$) electroplating system was employed as the mass transfer system. The mass transfer coefficient (h_m) can be calculated from the bulk concentration C_b and the limiting current density I_{lim} in eq. (1). Further details of this methodology can be found in Chung et al. [6, 7].

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

3.3 Numerical Methodology

In order to investigate the detailed cell behaviors according to cooling condition and height of side wall, a numerical study was carried out using the commercial CFD program FLUENT 6.3 [8]. The simulations were carried out using the Boussinesq approximation, and the temperature of the heated wall, the cooled wall, and an interior fluid was maintained at 400 *K*, 200 *K*, and 300 *K*, respectively. The test matrix for the experimental study is presented in Table 1.

4. Results and discussion

Figure 3 compares the experimental results with existing heat transfer correlations. The experimental results agreed well with the heat transfer correlations of Dropkin and Somerscales [9] and Globe and Dropkin [10]. The other correlations showed smaller Nusselt numbers than the current experimental results. However, their slopes were similar, which means that the effect of Ra_H to those Nusselt numbers is similar.

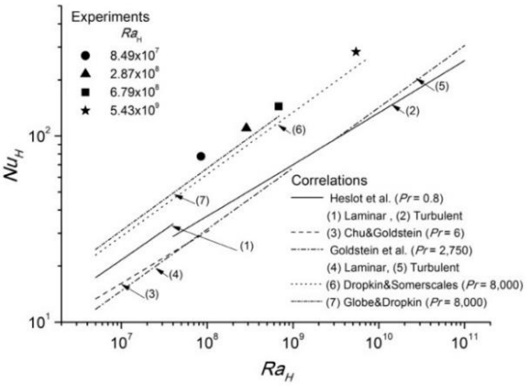


Fig. 3. Comparison of the test results with the Rayleigh-Benard natural convection.

Figure 4 presents the variation of mass transfer coefficient (h_m) according to aspect ratio (*H/R*). The mass transfer coefficient (h_m) was measured at the bottom plate. The heat transfer was enhanced by decreasing the aspect ratio (*H/R*) due to increase of the interaction between the heated and cooled plumes. Comparison of top cooling only and top+side cooling reveals that more heat is transferred to the side wall (Focusing effect) than the top plate. Also, the side wall cooling only cases show much higher heat transfer than other cases. This means that the top cooling in a severe accident condition reduces the heat focusing to the side walls.

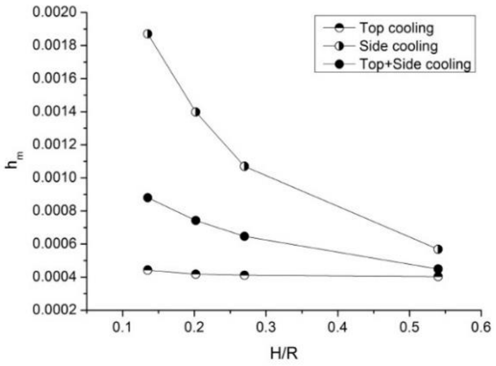


Fig. 4. h_m according to the aspect ratio (*H/R*).

Figure 5 shows comparison of the experimental and numerical results. The numerical results agree well with the experimental results. The error is less than 5%.

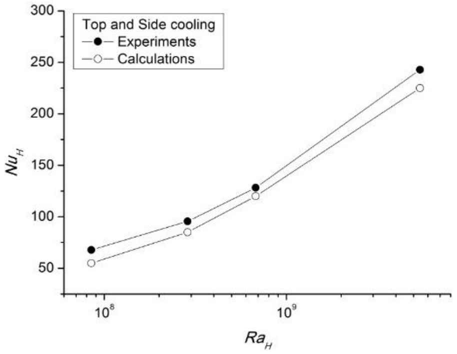
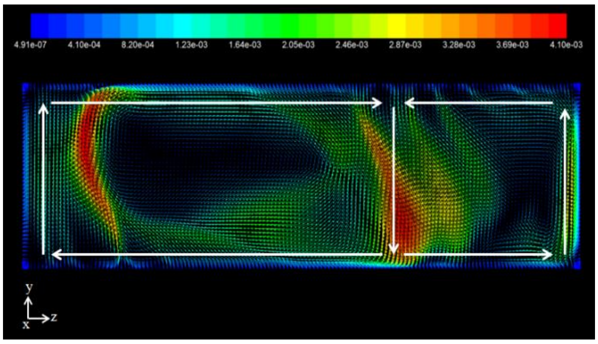
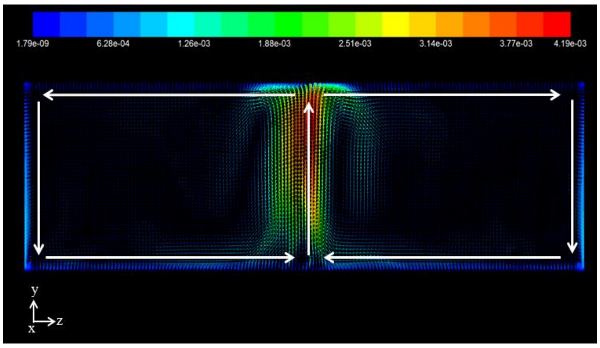


Fig. 5. Comparison of the experimental and numerical results.

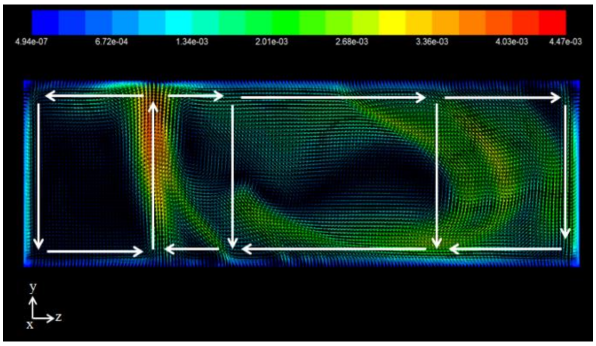
Figure 6 presents the variation of cell pattern in the three configurations: (a) top plate cooling, side wall adiabatic, (b) top plate adiabatic, side wall cooling, (c) both walls cooling. The height (*H*) is 0.04m. The "Focusing effect" is affected by the cell pattern (cell size, cell direction, central location of cell). Fig. 6(a) ~ (c) shows that cell pattern differs in the each cooling condition. In case of Top+Side cooling (Fig. 6(c)), the number of cell increases than other cases due to the interaction between heated and cooled plumes.



(a) Top cooling only



(b) Side cooling only



(c) Top+Side cooling

Fig. 6. Velocity vector depending on cooling condition.

5. Conclusions

The experimental and numerical studies were performed to investigate the focusing effect according to cooling condition of upper boundary and the height in metallic layer. The height of the side wall was varied for three different cooling conditions: top only, side only, and both top and side. Mass transfer experiments, based on the analogy concept, were carried out in order to achieve high Rayleigh number.

The experimental results agreed well with the Rayleigh-Benard convection correlations of Dropkin and Somerscales [9] and Globe and Dropkin [10]. The heat transfer on side wall cooling condition without top cooling is highest and was enhanced by decreasing the aspect ratio.

The numerical results agreed well with the experimental results. Each cell pattern (cell size, cell direction, central location of cell) differed in the cooling condition. Therefore, it is difficult to predict the internal flow due to complexity of cell formation behavior.

In order to mitigate the focusing effect, the control of the cooling condition of upper boundary in metallic layer and enough thickness of metallic layer are required.

Acknowledgment

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