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Measurement of the Cupric Ion Concentration in the Simulation of the Focusing effect

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1. Introduction

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 top and side walls (Fig. 1). During the IVR, 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 [1~3].

This study investigated the focusing effect depending on the different temperature conditions and height of side wall experimentally. 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. In order to simulate the different temperature conditions of top and side wall, an electrical resistance was attached to the top wall so that it is mimics hotter wall condition.

The heat transfer experiments were replaced by mass transfer experiments based on the 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.

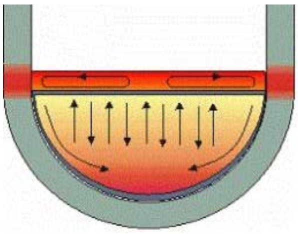


Fig. 1 Distribution of relocated molten core material.

2. Experiments

2.1 Experimental Methodology

Heat and mass transfer systems are analogous, as they are described by the same mathematical formulations with the same class of boundary conditions [4]. A sulfuric acid-copper sulfate (H_2SO_4-$CuSO_4$) electroplating system was employed as the mass transfer system. The transfer of cupric ions from the copper anode to the cathode submerged in an aqueous solution of sulfuric acid and copper sulfate is analogous to the transfer of heat.

The mass transfer coefficient (h_m) can be calculated from the bulk concentration C_b, the surface concentration C_s and the current density I in eq. (1). Further details of this methodology can be found in Chung et al. [5, 6].

$$h_m = \frac{(1-t_{Cu^{2+}})I}{nF(C_b - C_s)} \quad (1)$$

2.2 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 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 is 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. The Prandtl number was 2,014 and the radius of tank is fixed as 0.074m. In order to control the temperature conditions of top and side wall, the electrical resistance was attached to the top walls. The height of side wall and the electrical resistance are varied.

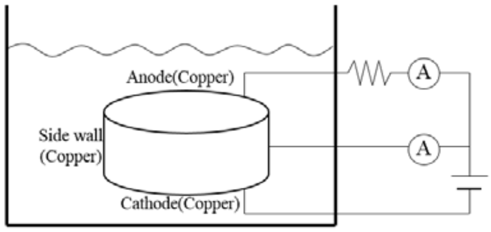


Fig. 2. The experimental apparatus.

Table I: Test matrix.

Pr	*R*(m)	*H*(m)	*H/R*	Ra_H	*Resistance*
2,014	0.074	0.01	0.135	8.49×10^7	1.5 Ω,
		0.015	0.202	2.87×10^8	3 Ω,
		0.02	0.270	6.79×10^8	4.7 Ω,
		0.04	0.541	5.43×10^9	10 Ω

3. 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 [7] and Globe and Dropkin [8]. 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.

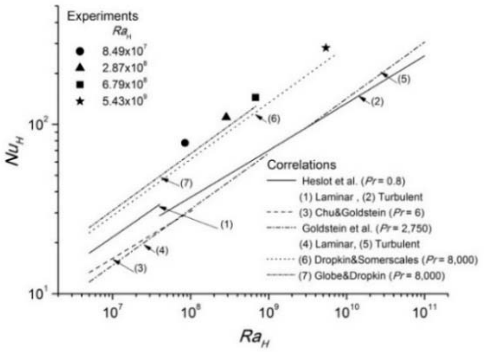
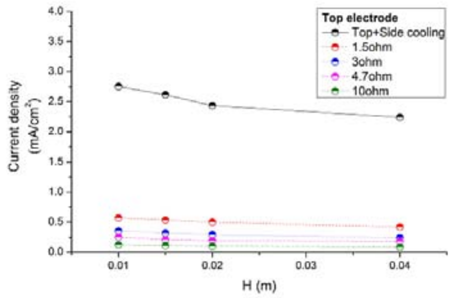


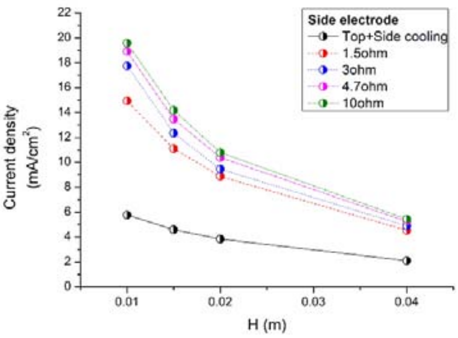
Fig. 3. Comparison of the test results with the Rayleigh-Benard natural convection.

Figure 4 shows the variation of current density according to height of side wall. In the Fig. 4(a) and (b), the current density (*I*) was measured at the bottom plate and side wall, respectively.

The heat transfer increased by decreasing the height of side wall due to increase of the interaction between the heated and cooled plumes. Comparison of top electrode and side electrode with the electrical resistance reveals that more heat is transferred to the side wall (Focusing effect) than the top plate. Namely, the hotter top wall condition improves focusing effect at the side wall.



(a) Top electrode



(b) Side electrode

In electroplating systems, the mass transfer coefficient is calculated based on the measured electric current and the difference in the cupric ion concentration. Through the concentration change in the mass transfer, the temperature conditions wall be revealed. As it is difficult to measure the cupric ion concentration at the cathode surface, the methodology development is necessary. In order to measure the cupric ion concentration in the copper plate, this study investigates the method of concentration measurement: RGB (Red, Green and Blue), Brightness, ICP (Inductively Coupled Plasma), and PIV (Particle Image Velocity).

4. Methodology development

4.1 Apparatus and test matrix

Figure 3 shows the test rig for the measurement of cupric ion concentration. The test section is a rectangular tank made of acryl. In order to minimize the refraction of light, the thickness of acryl is 0.005m. Each side wall simulates heated wall and cooled wall. In order to establish a known, the simple geometry, the vertical plate was used.

The test matrix shown in Table II. The Rayleigh number ranged from 1.06×10^{10} to 2.87×10^{11}. The mass transfer experiments were carried out using a sulfuric acid–copper sulfate (H_2SO_4–$CuSO_4$) electroplating system.

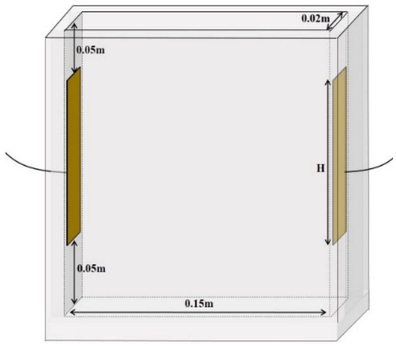


Fig. 3. The test rig of concentration measurement.

Table II: Test matrix for concentration measurement.

Pr	***W*(m)**	***H*(m)**	***Ra$_H$***
2,014	0.02	0.05	1.06×10^{10}
		0.10	8.49×10^{10}
		0.15	2.87×10^{11}

4.2 RGB Method

RGB (Red, Green and Blue) refers to a system for representing the colors to be used on a display. Red, green and blue can be combined in various proportions to obtain any color in the visible spectrum. The red, green and blue light are combined to make millions of colors [9].

In order to analyze the variation of the cupric ion concentration using RGB method, the images corresponding to the thermal boundary layer are needed. As Prandtl number is very high in this study, the thermal boundary layer becomes smaller about 0.2×10^{-3} m. So an optical microscope was used to obtain a high-magnification and high-resolution image. Figure 4 shows the test image for the height of 0.01m. Even as the voltage was applied the transparent layer was formed by concentration change of the cupric ion. Brightness and PIV method are similar to this process.

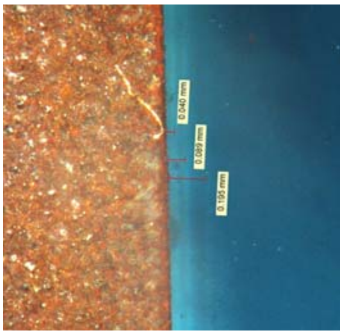


Fig. 4. The test image using the optical microscope.

4.3 ICP Method

An inductively coupled plasma (ICP) can be generated by directing the energy of a radio frequency generator into a suitable gas, usually ICP argon. Other plasma gases were used such as Helium and Nitrogen. ICP can be very powerful tools for detecting and analyzing trace elements [10].

In order to analysis the cupric ion concentration using ICP method, the solution samples were taken from the electrode surface. The process is as follows: (a) 1~10μl of the solution is taken using micro pipet due to the smaller thermal boundary layer, (b) the sample was diluted with distilled water because the minimum quantity of ICP test sample is 10ml, (c) after the preprocessing, the analysis of samples starts.

Figure 5 presents the cupric ion concentration using the spectrophotometer. The case of base (black line) is the distilled water. So, the cupric ion concentration is zero. The bulk case (red line) is the sulfuric acid–copper sulfate (H_2SO_4–$CuSO_4$) solution. This case shows the maximum value among others. The case of 300mV (blue line) and 600mV (Pink line) is an initial voltage and the voltage of limiting current range, respectively. The cupric ion concentration of the initial voltage is similar to bulk solution. And then the value of limiting current range becomes smaller. The variation of the cupric ion concentration was confirm by this method.

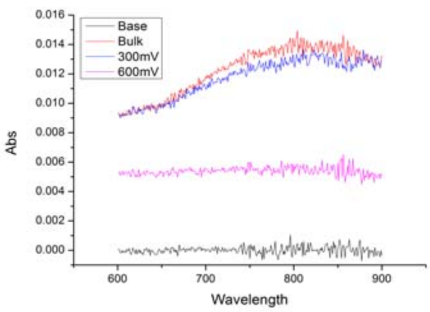


Fig. 5. The results for the spectrophotometer.

5. Conclusions

The experimental study was performed to investigate the focusing effect according to the different temperature conditions and the height in metallic layer. This work devised a method to simulate the different cooling conditions of the top and side walls and adopted an electrical resistance to the top plate. The electrical resistance was varied for the height of side wall.

The experimental results agreed well with the Rayleigh-Benard convection correlations of Dropkin and Somerscales [9] and Globe and Dropkin [10]. The heat transfer was enhanced by increasing the electrical resistance and decreasing the height of side wall. The focusing effect at the side wall was improved by the hotter top wall condition.

In order to overcome the limitations of mass transfer, this work tried to measure the cupric ion concentration. The methods of concentration measurement are RGB, Brightness, ICP and PIV. The key of RGB, Brightness and PIV method is the clear images of the thermal boundary layer. The results for ICP method can be got by taking the trace sample of a solution, accurately. The methodology of concentration measurement is still under development stage.

In order to develop the methodology of concentration measurement, the improved photographic technique and accurate sampling are required.

Acknowledgment

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