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# Mass transfer Simulation of Two-dimensional Natural Convection of Mixture Layer in an IVR

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## 1. Introduction

In a severe accident, the fuels melt down and relocate in the reactor vessel by the density difference. The molten core is stratified as upper metallic layer and lower mixture layer. The technical concern is decay heat cooling to retain the molten core in vessel (IVR-ERVC: In-Vessel Retention-External Reactor Vessel Cooling). This study is focusing on the angle dependent heat flux distribution at the reactor vessel plenum due to mixture layer natural convection experiment.

We simulated heat transfer using a sulfuric acid–copper sulfate ($H_2SO_4$–$CuSO_4$) electroplating system based on the heat and mass transfer analogy concept. An S-bend shaped copper is used as the volumetric heat source, which is simulated as a heater in previous heat transfer studies. The advantage of mass transfer experiment is the achievement of the high buoyancy condition similar to reactor vessel because of high *Pr*.

## 2. Theoretical Background

### *2.1 Definition of $Ra'_H$*

Since, the mixture layer radiates decay heat continuously, we have to establish interal heat generation. A natural convection heat transfer phenomena involving volumetric heat source is described by $Ra'_H$ instead of $Ra_H$.

$$Ra'_H = Ra_H \times Da \ , \tag{1}$$

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

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

### *2.2 Previous studies*

#### *2.2.1 Two-dimensional experiments*

Lee et al. [1] investigated natural convection heat transfer from mixture layer in a two-dimensional semi-circular pool (SIGMA CP). They used S-shaped electrode as a volumetric heat source to achieve $Ra'_H$ of $5.71\times10^6$ and $7.04\times10^{11}$. The working fluids were Air and water. The heat flux on the side of the upper plate is approximately 20-25% larger than on that center of the upper plate in both air and water as working fluids. The heat flux at lower plenum increases up when the pool angle increases and has a peak between 80° and 90°. They also developed heat transfer correlations as below:

$$Nu_{up} = 0.31(Ra'_H Pr^{-0.36})^{0.245} \tag{4}$$

$$Nu_{dn} = 0.219(Ra'_H Pr^{-0.215})^{0.235} \tag{5}$$

Bonnet and Seiler [2] studied natural convection heat transfer from mixture layer in a two-dimensional semi-circular experiment facility (BALI). They used the lattice shaped wire electrode as the volumetric heat source with $Ra'_H$ of $10^{15}$ – $10^{17}$. The working fluid was water adding cellulose. The isothermal condition was established at the inner wall of the pool by outer coolant circulation. The heat flux at lower plenum increases up to the equator when the pool angle increases. They developed correlations for *Nu* of the top plate ($Nu_{up}$) and the curvature ($Nu_{dn}$) and as below:

$$Nu_{up} = 0.383\ Ra'^{0.233}_H \tag{6}$$

$$Nu_{dn} = 0.116\ Ra'^{0.25}_H \tag{7}$$

#### *2.2.2 Three-dimensional experiments*

Suh et al. [3] simulated SIGMA CP study as three-dimensional experiment using hemispherical pool (SIGMA 3D). Volumetric heat source is arranged several S-shaped electrodes similar to SIGMA CP experiment. The fluid is air and water. The experiment is performed in the $Ra'_H$ range of $4.46\times10^6$ – $3.5\times10^{10}$. When the working fluids were both air and water, the upper heat flux distributions were irregular depending on the position. When the pool angle increases, the heat flux at lower plenum increases up peaking nearly in 80° and then drops.

A. Palagin and Kretzschmar [4] investigated natural convection heat transfer of the mixture layer using three-dimensional hemispherical pool. They used array of ring-shaped wire electrodes as a volumetric heat source and water as working fluid. The experiment was performed in a single value $Ra'_H$ of $1.2\times10^{14}$. In result, heat flux increases up when the pool angle increases. The heat flux result vicinity of the top plate was absent because the level of working fluid in the pool did not reached the top.

## 3. Experiments

### *3.1 Methodology*

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

A mass transfer experiment using the electroplating system is performed first by Levich [5], and Selman [6] organized mass transfer correlations under different conditions after that. A more detailed explanation of the methodology can be found in Chung et al [7]. Because it is difficult to know the concentration of copper ion on the cathode surface, we used limiting current technique. When the potential between electrodes increases continuously, the current increases until the plateau section, which is steady despite the potential increase. The current in plateau section is the limiting current. In limiting current, the concentration of copper ion on the cathode surface is almost zero. Therefore, mass transfer coefficient $h_m$ is defined as below.

$$h_m = \frac{(1-t_{Cu^{2+}})I_{\lim}}{nFC_b} \tag{8}$$

Because buoyancy towards bottom of the facility is formed in heat transfer, cold wall of the pool could be simulated as anode in mass transfer. However, the limiting current is not measured in anode. [8] Therefore we performed the experiment using facility inverted against the gravity direction and simulated cathode as cold wall.

### *3.2 Experimental facility*

Figure 1 is the experimental facility of MassTER-OP2 (Mass Transfer Experimental Rig - Oxide Pool 2 dimensional experiment) and S-shaped heat source. The experimental facility is two-dimensional semi-circular pool. The height, length and width are 10cm, 20cm and 4cm respectively. Previous numerical experiment by Dinh et al [9] describes to ignore the side wall effect when Δx/h is larger than 0.25. In this study, It is satisfied that Δx=4cm, h=20cm and Δx/h =0.4. The copper is placed on the inner wall of upper and curved side. In order to measure local current, half of the copper is divided by 4pieces on upper side and 9 pieces on curved side. Volumetric heat source is fixed on the flat side wall. The facility is filled with sulfuric acid–copper sulfate ($H_2SO_4$–$CuSO_4$) fluid. Figure 2 shows the system circuit. The multi-meter is connected with cathode copper in parallel.

Table1 shows the test matrix.

Figure 1. Experimental facility and S-bend heat source

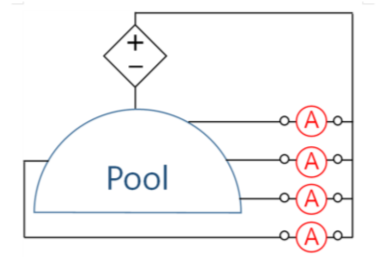


Figure 2. Experimental circuit

Table 1. Test matrix for experiments

| ***Volumetric heat source*** | ***Pr*** | ***Ra'$_H$*** | ***Pool Top*** |
|---|---|---|---|
| S-bend | 2,014 | $3\times10^{14}$ | Isothermal |
| | | | insulated |

## 4. Results and discussion

### *4.1 Comparison of average Nu with previous experiments*

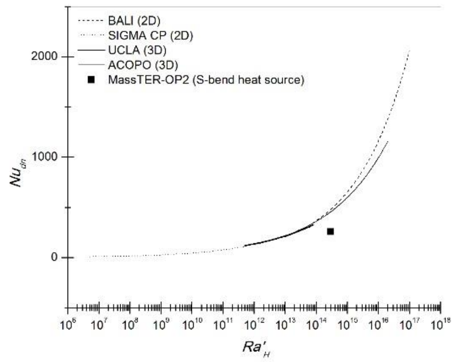


Figure 3. A comparison of vessel surface $Nu_{dn}$ with respect to $Ra'_H$

Figure 3 compares the experimental results $Nu_{dn}$ with existing heat transfer correlations. The $Nu_{dn}$ of MassTER-OP2 is little lower than other correlations, but the difference is small.

### *4.2 Comparison of Nu distribution with SIGMA CP*

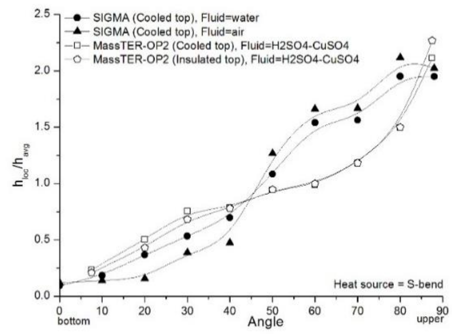

Figure 4. Comparison of *Nu* depending on curved surface angle between MassTER-OP2 and SIGMA

Figure 4 compares *Nu* for MassTER-OP2 with for SIGMA CP. It is possible to compare only for relative *Nu* according to curved surface angle because vertical axis showed $h_{loc}/h_{avg}$. Both MassTER-OP2 and SIGMA experiments used S-shaped heat source. We used sulfuric acid–copper sulfate ($H_2SO_4$–$CuSO_4$) for fluid and *Pr*=2,014. SIGMA used water and air for fluids. They performed in the *Pr* range of 4 – 8 for water and *Pr*=0.7 for air. We performed two case that each condition was cooled top and insulated top. However SIGMA performed experiments only when top is cooling.

Both MassTER-OP2 and SIGMA results indicate *Nu* rises as the angle of curvature surface increases. The maximum *Nu* was located at uppermost curvature surface for MassTER-OP2. However *Nu* peaked at 80° and slightly decreased at 80°– 90° section for SIGMA. It is because *Pr* for MassTER-OP2 is much higher than for SIGMA. In uppermost curvature, boundary layer of top and curvature surface overlap each other. Overlapped boundary layer in high *Pr* is thinner than in low *Pr*. In result, Peak for MassTER-OP2 appears uppermost section differently from SIGMA.

## 5. Conclusions

This study performed mass transfer experiment using a sulfuric acid–copper sulfate ($H_2SO_4$–$CuSO_4$) electroplating system based on the heat and mass transfer analogy concept. The experimental result was compared with previous 2D study (SIGMA CP). The results of MassTER-OP2 were similar to that of SIGMA CP except for upper section of curvature surface. The difference of the results in upper section is due to difference of *Pr*.

In further study, we plan to perform experiments by changing size and shape of volumetric heat source. And we will compare the results with 3D experiment.

## ACKNOWLEDGMENT

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## REFERENCES

[1] J. K. Lee et al., Experimental study of natural convection heat transfer in a volumetrically heated semicircular pool, Annals of Nuclear Energy, Vol.73, pp. 432-440, 2014.

[2] J. M. Bonnet and J.M. Seiler, Thermal hydraulic phenomena in corium pools: The BALI experiment, 7th International Conference on Nuclear Engineering, Tokyo, Japan, 1999.

[3] K. Y. Suh et al., In-vessel retention strategy for high power reactors, Korea Electrical Engineering & Science Research Institute, Korea, 2005.

[4] A. Palagin and F. Kretzschmar, LIVE test FSt4: experimental results and simulation by CONV code, The 13th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, Knanazawa City, Japan, 2009.

[5] V. G. Levich, Physicochemical Hydrodynamics, Prentice Hall, Englewood Cliffs & NJ, 1962.

[6] J. R. Selman, *et al.*, Advances in Chemical Engineering, 10th, Academic Press, New York and London, 1978.

[7] B.J. Ko, W.J. Lee, B.J. Chung, Turbulent mixed convection heat transfer experiments in a vertical cylinder using analogy concept, Nucl. Eng. Des., Vol. 240, pp. 3967-3973, 2010.

[8] Y. Konishi *et al*., Anodic dissolusion phenomena accompanying supersaturation of copper sulfate along a vertical plane copper anode, *Electrochimica Acta*, 48, 2615-2624, 2003.

[9] T.N. Dinh, R.R. Nourgaliev, B.R. Sehgal, On heat transfer characteristics of real and simulant melt pool experiments, Nucl. Eng. Des., Vol.169, pp.151-164, 1997.