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Utilization of Analogy Experimental Method for the Severe Accident Studies

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1. Introduction

The studies on the severe accident phenomena are engaged with tough experimental conditions such as high temperature, high pressure, high heat flux, highly buoyant condition, etc. Experimental studies using real materials are desirable but they are expensive and dangerous.

This paper suggests an experimental methodology applicable to highly buoyant or extreme test conditions based on the analogy between heat and mass transfer. The copper-sulfate electroplating system is employed as the mass transfer system. In the system, when the potential is applied, the cupric ions are transferred from anode to cathode and they work as the transferred heat in the heat transfer system. The amount of reduced cupric ions is easily and accurately measured by the electric current measurement. The reduction of the cupric ion concentration near the cathode causes buoyant force. Using this system, high buoyance can be established with relatively small test rig.

This paper summarizes some papers of the authors to introduce the methodology regarding the In-Vessel Retention via External Reactor Vessel Cooling (IVR-ERVC) situation, Reactor Cavity Cooling System (RCCS) and Critical Heat Flux (CHF) phenomenon.

2. Analogy between Heat and Mass Transfer

Heat and mass transfer systems are analogous as the mathematical models describing the two phenomena are of the same form [1]. Therefore, although the two phenomena are different in nature, these can be treated mathematically as the same. Table 1 summarizes the governing parameters for heat and mass transfer systems. Here we suggested is copper sulfate-sulfuric acid ($CuSO_4$-H_2SO_4) electroplating system. This system have been well established in several decades by the pioneers. In this system, the ionic concentration gradient causes buoyancy force which achieves high Rayleigh number with relatively short length scale. Moreover, the measurements are achieved by the electric circuit which is superb in terms of the accuracy relatively to the other measurement tools. Thus, applying this methodology for the nuclear power plant systems, the high buoyant-induced systems can be simulated readily using compact test rig. This technique was developed by several researchers [2–5], and the methodology is well-established [6–13]. Compared with temperature measurements, this technique is attractive as it provides a simple, low-cost, accurate method through the electric current measurement [14, 15].

Table I: Corresponding Governing Parameter

Heat transfer	Mass transfer
$Pr=\dfrac{\nu}{\alpha}$	$Sc=\dfrac{\nu}{D_m}$
$Nu=\dfrac{h_h H}{k}$	$Sh=\dfrac{h_m H}{D_m}$
$Ra=\dfrac{g\beta\Delta T H^3}{\alpha\nu}$	$Ra=\dfrac{gH^3}{D_m\nu}\dfrac{\Delta\rho}{\rho}$

Figure 1 depicts the schematic of $CuSO_4$-H_2SO_4 electroplating system. In this system, cupric ions are reduced at the cathode surface. The resulting decrease in the cupric ion concentration in the solution induces a buoyant force. Thus the cathode is used as the hot wall. To minimize the electric migration of the cupric ions, sulfuric acid is added as the supporting electrolyte to increase the electric conductivity of the solution.

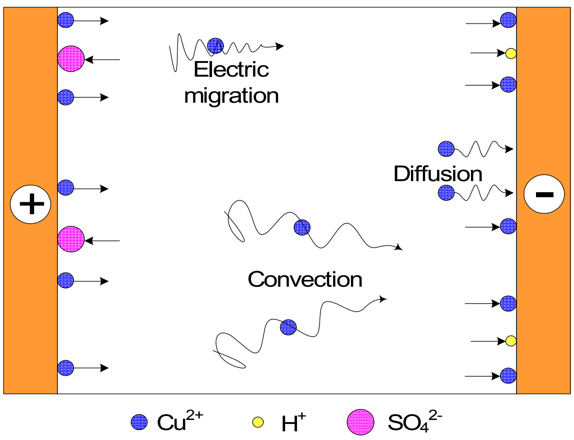


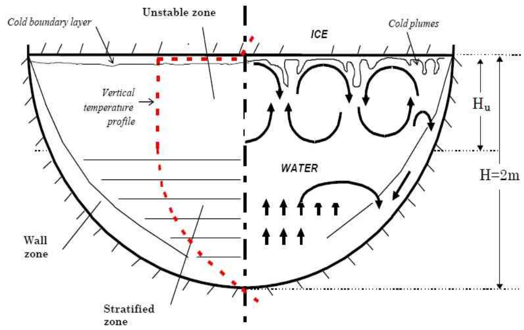
Fig. 1. Ionic transfer in the copper electroplating system.

3. Applications to Severe Accident Studies

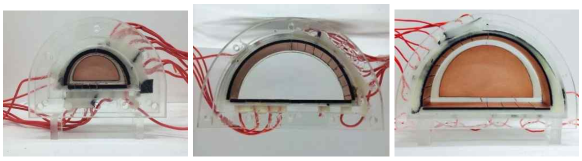
3.1 In-Vessel Retention (IVR)

We conducted the natural convection experiments simulating the oxide pool in the IVR-ERVC situation using Mass Transfer Experimental Rig for Oxide Pool

(MassTER-OP) [13, 16]. The modified Rayleigh number of over 10^{15} was established with all of 0.167 m test rig. Fig. 2 shows the test rigs to simulate the phenomena. Tests were performed at the inverted arrangement to use the cathode for the measurements. And piece-wise electrodes enable to measure local average values and then phenomenological analysis can be performed. MassTER-OP simulate with 2D and 3D test rigs.



(a) General flow patterns of the oxide pool [17]



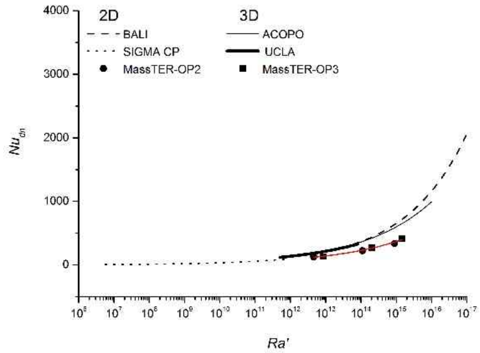
H=0.042 m H=0.1 m H=0.167 m

H=0.042 m H=0.1 m H=0.167 m

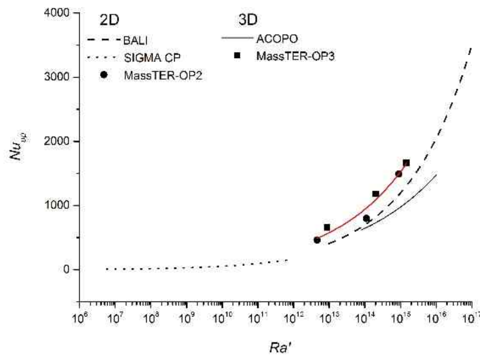
(b) 2D and 3D test rigs for simulate oxide pool

Fig. 2. Oxide pool phenomena and test rigs.

Nusselt numbers (*Nu*) at the curved surface of the reactor vessel and boundary between oxide pool and metallic layer (Top plate) were measured and compared with existing heat transfer results both 2D and 3D experiments. As shown in Fig. 3, the lower *Nu*'s were measured at the curved surface and the higher *Nu*'s were measured at the top plate both 2D and 3D cases. These results were caused by difference of the Prandtl number (*Pr*). The higher *Pr*, the higher *Nu* of the top plate were measured. Fig. 4 shows the angular *Nu* ratios compared with existing studies. The general trends were similar but small discrepancies occurred at the uppermost region. The authors insisted that difference of *Pr* and geometrical feature influenced the results. Further details of these results can be found in the corresponding papers [13, 16].

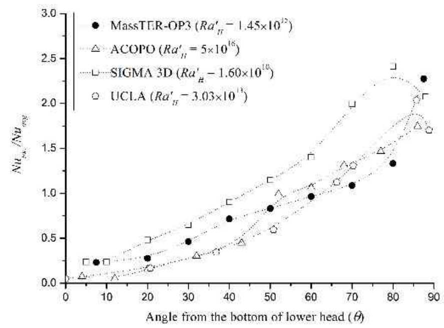


(a) Mean *Nu* of the curved surface.

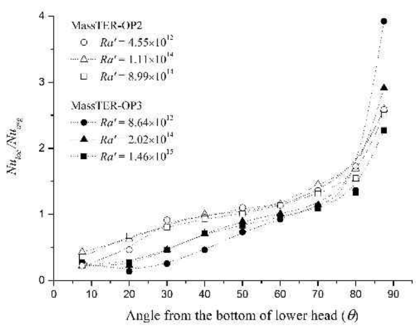


(b) Mean *Nu* of the top plate.

Fig. 3. Comparison of mean Nu's for the curved surface and top plate.



(a) Comparison of the existing studies.



(b) Comparison of the 2D and 3D results.

Fig. 4. Local Nu ratios along the curved surface.

3.2 Reactor Cavity Cooling System (RCCS)

In the RCCS, where highly buoyant flows are induced in a duct geometry, the flow regime becomes similar to the mixed convection. As shown in the Fig. 5, the authors conducted mixed convection tests using a simple circular geometry in order to explore the fundamental phenomenon. Grashof number of over 10^{10} was achieved with the vertical pipe of less than 1 m. The empirical correlation was developed by varying the height of vertical pipe, as shown in Eq. (1). Also the experiments were performed to investigate the impairment of local heat transfer in a vertical pipe. Fig. 6(a) shows the average heat transfers of buoyance aided and opposed flows according to the Buoyancy coefficient. Fig. 6(b) shows the non-monotonous behaviors of the mixed convection heat transfer along test section. Heat transfer decreases due to entrance effect during developing and enhances by the transition. In the turbulent mixed convection, buoyancy-aided flow showed an impairment of the heat transfer along the axial position due to the laminarization. And then, the heat transfer was enhanced as increasing buoyancy forces since the recovery of turbulence production. For this reason, mixed convection phenomenon of the cooling system must be established. Further details of these results can be found in the corresponding papers [18, 19].

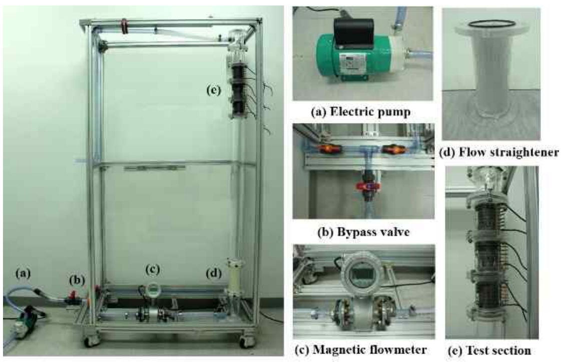
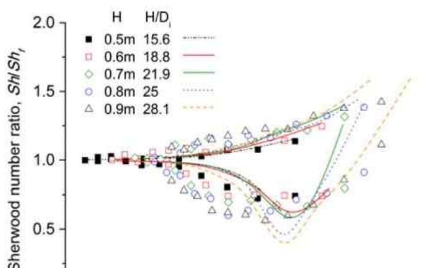
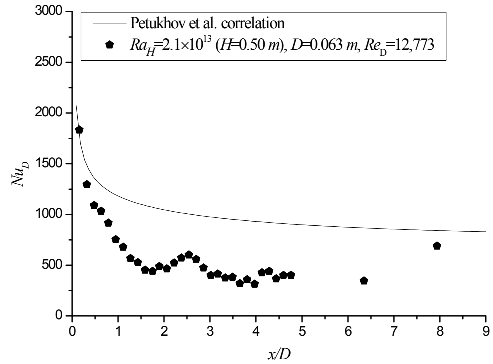


Fig. 5. Experimental test rig for mixed convection



(a) Mean Sh ratio with respect to the Bo



(b) Local Nu with respect to the elevation

Fig. 6. *Mean and local heat transfer at a vertical pipe.*

$$\frac{Sh}{Sh_f}=\left\{1\pm f(H/D_i)Bo\left(\frac{Sh}{Sh_f}\right)^2\right\}^{0.52},$$

where $f(H/D_i)=-205.95(H/D_i)^2+7.89\times10^3(H/D_i)+3.45\times10^3$.

3.3 Critical Heat Flux (CHF)

Many studies have been performed for Critical Heat Flux (CHF) in last several decades. The experiments are not easy due to the extremely high temperature and controlling difficulty caused by thermal inertia. We simulated boiling condition with the electroplating system. At a low electric potential, only the cupric ions are reduced at the cathode. But at a high electric potential, hydrogen ions in the solution reduces and forms a gas plume over the cathode surface and thus two-phase flow behaviour can be simulated by two-component flow. In spite of the difference between two-phase and two-component system, the prime phenomena of the CHF situation were observed and measured by Jeong *et al*. [20]. In these point of view, authors conducted experiment with horizontal copper plate. The sudden drop of the measured electric current occurred, which similar to the CHF phenomenon as shown in Fig. 7 and took photographs in stepwise current value (a)-(d) and compared with the results by Ahn and Kim [21] (e)-(h) as shown in Fig. 8.

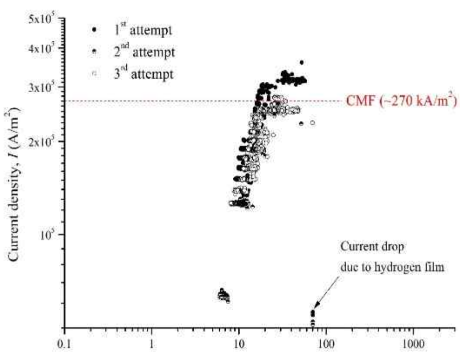
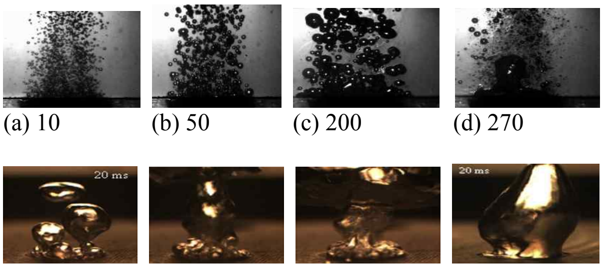


Fig. 7. Measured currents with respect to the potential.



(a) 10 (b) 50 (c) 200 (d) 270

(e) 100 (f) 400 (g) 1,400 (h) 1,500

Fig. 8. Hydrogen bubble behaviors (kW/m^2).

4. Conclusions

Several nuclear safety systems were simulated using electroplating system: IVR situation, RCCS and CHF phenomenon. Highly buoyant conditions were tested with compact size facilities. The results were compared with the existing heat transfer results and well agreed with them. The authors figured out the basic heat transfer characteristics and flow regime of the oxide pool and mixed convection problems. Moreover, the fundamental phenomenological study have conducted using piece-wise cathode. And this electroplating system is applicable to boiling problem such as CHF phenomenon and will be developed in further works.

Although the results by the electroplating system would not be able to be accepted by the regulatory body, the authors expected that the preliminary verification of the system can be performed with the methodology.

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