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The Measurements of Natural Convection Heat Transfer in Enclosures Using Analogy Experimental Methodology

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1. Introduction

Hydrogen is arousing interests as the viable, clean, future energy source. However it will be clean as long as its production method does not impose environmental burdens. One of the promising production methods of hydrogen is to use the heat from an HTGR (High Temperature Gas-cooled Reactor). However the gas coolant, of which less experience has been accumulated, requires a more detailed knowledge of heat transfer phenomena: Due to its relatively low heat capacity, the radiation heat transfer fraction increases. The property changes sensitive to the temperature causes the significant buoyancy effect [1].

High and expensive facilities are needed to simulate the high-buoyancy phenomena. Heat leakage from test facility to structural materials is also unavoidable. However, in order to overcome those problems, an experimental methodology using analogy concept has been developed [2]. This study, as the extended study for the further development of the methodology, simulates the natural convection in enclosures for the various Rayleigh numbers and aspect ratios(*H/L*) and measures the heat transfer rates.

2. Phenomena and Methodology

2.1 Natural convection in enclosures

Buoyancy-driven flows in enclosures with vertical heated walls have been a topic of continuing interest because of their fundamental importance and of their applications in a number of areas, such as heating and cooling of buildings, the cooling of electronic components and nuclear reactors, etc. [3]. The traditional natural convection problem in an enclosure composed of vertical heated and cooled walls and two adiabatic top and bottom, is divided into four heat transfer regimes according to the aspect ratio and Ra number: conduction limit(Ra ~ 0), tall enclosure limit($H/L > Ra^{1/4}$), high-Ra limit(boundary layer regime;$Ra^{-1/4} < H/L < Ra^{1/4}$) and shallow enclosure limit($H/L < Ra^{-1/4}$).

The heat transfer in the high-Ra limit and shallow enclosure limit is dominated by the convection, while the major mechanism is the conduction in conduction limit and tall enclosure limit [4].

2.2 Analogy between heat and mass transfer

It is well-known that heat transfer and mass transfer systems are analogous mutually under same initial and boundary conditions. With the concept, these systems can be transformed to each other theoretically. Therefore, the heat transfer result can be obtained directly from the mass transfer result through the dimensionless group transformations (Table 1).

Table 1. Dimensionless group for analogy.

Heat transfer		Mass transfer	
Nusselt number	$\frac{hd}{k}$	Sherwood number	$\frac{h_m d}{k}$
Prandtl number	$\frac{\nu}{\alpha}$	Schmidt number	$\frac{\nu}{D_m}$
Rayleigh number	$\frac{g\beta \Delta T H^3}{\alpha \nu}$	Rayleigh number	$\frac{gH^3}{D_m \nu}\frac{\Delta\rho}{\rho}$

2.3 Electroplating System

A copper electroplating system was employed to simulate the natural convective heat transfer in enclosures. The electrolytic cell was filled with electrolyte solution of $CuSO_4$ and H_2SO_4. The electrical circuit was composed as shown in figure 1.

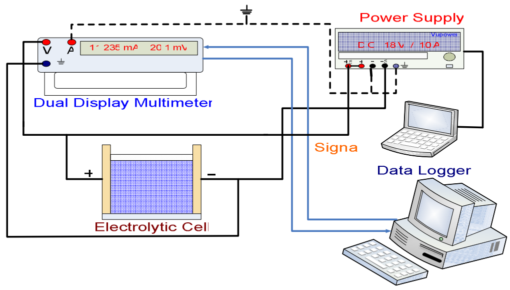

Figure 1. Electrochemical system circuit.

With the application of the electrical potential, copper ions discharged from anode move to the cathode. The flux of copper ions is simulating the heat flux. In this problem, as the solution near the cathode is lighter due to the low copper ion concentration, the cathode is simulating heated wall and the anode is cooled wall.

2.4 Limiting current technique

In the copper electroplating system, the mass transfer coefficient can be directly obtained from the concentration difference of copper ions between bulk and surface on cathode and also electric current between electrodes. However, it is extremely difficult to determine the surface concentration on cathode. The problem like this can be easily solved by using the limiting current technique, because the concentration of surface on cathode is considered as zero [5]. With increasing the applied potential, measured current increases rapidly and then reaches a certain current plateau: *limiting current region* (Figure 2).

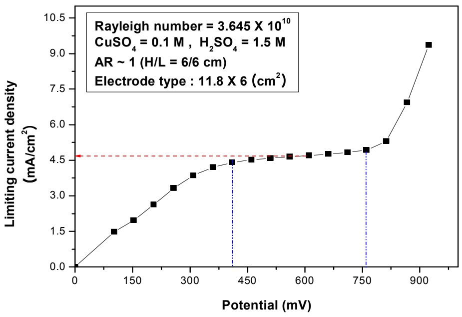

Figure 2. Typical limiting current curve.

3. Tests and Results

3.1 Test methods

This study was performed in boundary layer regime. Most studies so far has been devoted to the laminar region. However this study focused on high Ra boundary layer regime. The wide range of Ra numbers (10^7 ~ 10^{13}) was determined by controlling the $CuSO_4$ concentration and height of electrodes(H) under fixed length between electrodes(L). On the other hand, the effect of aspect ratios on the mass transfer rates was estimated by varying only the length between electrodes under fixed Ra numbers and height of electrodes. The range of aspect ratios is about 0.1 ~ 10.

3.2 Results

Figure 3 shows that the measured Sh numbers under fixed length between electrodes strongly depend on Ra number for each fixed aspect ratio.

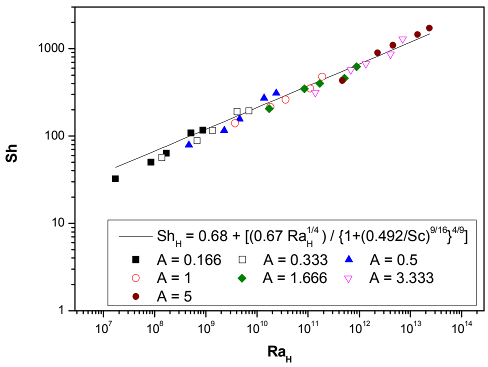

Figure 3. *Ra number* vs. *Sh number*.

It is estimated that mass transfer rates increase in proportion to Ra number according to the increase in height of electrodes and $CuSO_4$ concentration. And also, these test results show good agreement with the heat transfer correlation by S. W. Churchill, et al. [6].

However, as shown in figure 4, Sh number subject to the various aspect ratios for the fixed heights (fixed Ra numbers) remains unchanged. It means that the change in aspect ratio originated by the change of length between electrodes has no effect on mass transfer rates. These test results could be associated with the analysis estimated by Bejan [7]; in the boundary layer regime, the effect of aspect ratio, strictly the length between electrodes could be neglected. This interpretation is supported through the relatively good agreement between measured data and the related heat transfer correlation.

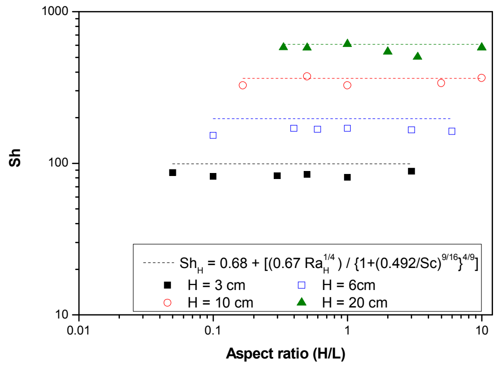

Figure 4. *Aspect ratio* vs. *Sh number*.

4. Conclusion

The natural convection heat transfer in enclosures was simulated using analogy experimental methodology. According to the various changes in Rayleigh number and aspect ratio, mass transfer experiments were conducted using electroplating system with limiting current technique for boundary layer regime of convective heat transfer. The result shows that mass transfer rate is greatly affected by Rayleigh number while aspect ratio has no influence. These results showed good agreements with the related heat transfer correlations.

Consequently, the analogy experimental methodology is expected to be a useful tool for heat transfer studies for HTGR as well as the systems with high-buoyancy phenomena.

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