An Experimental Study on Rayleigh-Benard Natural Convection

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1. Introduction

Core melt in a severe accident condition, forms a molten pool in the reactor vessel lower head. The molten pool is divided by a metallic pool (top) and an oxide pool (bottom) by the density difference. Due to the decay heat generated in oxide pool, Rayleigh-Benard natural convection heated from below and cooled from above occurs in the metallic pool [1].

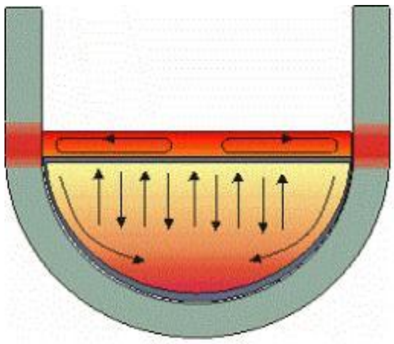


Fig. 1. Distribution of relocated molten core material.

Experiments were performed to investigate Rayleigh-Benard natural convection as a preparatory study before an in-depth severe accident study. The natural convection heat transfers were measured varying the plate separation distance and the area of plate with and without the side wall.

Using the analogy concept, heat transfer experiments were replaced by mass transfer experiments. A cupric acid–copper sulfate (H_2SO_4-$CuSO_4$) electroplating system was adopted as the mass transfer system and the electric currents were measured rather than the heat.

2. Previous studies

The natural convection heat transfers on upward- and downward-facing horizontal plates are well known. Eqs. 1 and 2 are the natural convection heat transfer correlations developed for the upward-facing horizontal plates by McAdams [2]. The characteristic length L_c is defined as the ratio of plate surface area *A* to perimeter *P* as $L_c=A/P$.

$$Nu_{L_c} = 0.54 Ra_{L_c}^{1/4} \quad (10^4 \le Ra_{L_c} \le 10^7) \tag{1}$$

$$Nu_{L_c} = 0.15 Ra_{L_c}^{1/3} \quad (10^7 \le Ra_{L_c} \le 10^{11}) \tag{2}$$

Oguz Turgut and Nevzat Onur [3] studied the natural convection of air between the heated lower and the insulated upper horizontal plates experimentally and numerically. The *Ra* ranged from 1,108 to 2.339×10^5. They focused on the influence of plate spacing and temperature difference. They reported that the effect of cover plate begins to diminish with the Separation distance and that the heat transfer increases with the temperature difference between the lower and the upper plates increases.

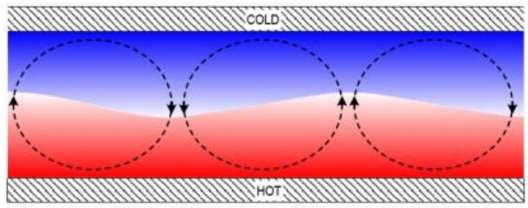


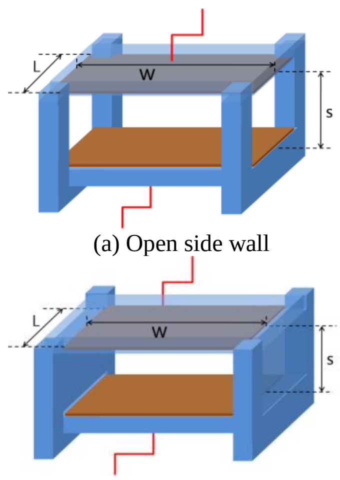
Fig. 2. Rayleigh-Benard natural convection flow

Fig. 2 shows the flow cells formed by ascending hot plume and descending cold plume in Rayleigh-Benard natural convection [4]. The flow cells are affected by Rayleigh number. Fundamental studies on the natural convection between the two horizontal plates, are rare and it is even more difficult to find researches of the topic in the turbulent flow region.

3. Experiments

3.1 Apparatus and Test Matrix

Fig. 3 shows test apparatus. The apparatus consisted of a downward-facing rectangular copper anode plate, an upward-facing copper cathode plate and acrylic supports of either open or closed sides, which is immersed in a solution tank of enough volume.



(b) Closed side wall

Fig. 3. The experimental apparatus.

Table 1: Test matrix.

Length (m)	Width (m)	Side wall	Separation distance (m)
0.05, 0.1	0.15, 0.2, 0.25	Open, Closed	0.005, 0.01, 0.02, 0.04, 0.06

Table 1 is the test matrix. Areas of plates, plate separation distances, and presence of side wall were varied accordingly. The Ra_s depending on the separation distance ranged from 1.06×10^7 to 1.83×10^{10} and Pr was 2014.

3.2 Experimental Methodology

Heat and mass transfer processes have analogy characteristic as the governing equations and parameters are of the same type [5]. Therefore, heat transfer problem can be solved by mass transfer experiment, or conversely. In this study, the measurements of mass transfer rates using limiting current technique were performed. A more detailed explanation of the methodology can be found in Chung et al. [6-7].

4. Results and discussion

Fig. 4 shows the measured Nu_{Lc} varying the separation distances with/without the side walls for several different plate areas. Test results for a single upward-facing plate were denoted and compared with existing heat transfer correlation developed by McAdams and they were in good agreements.

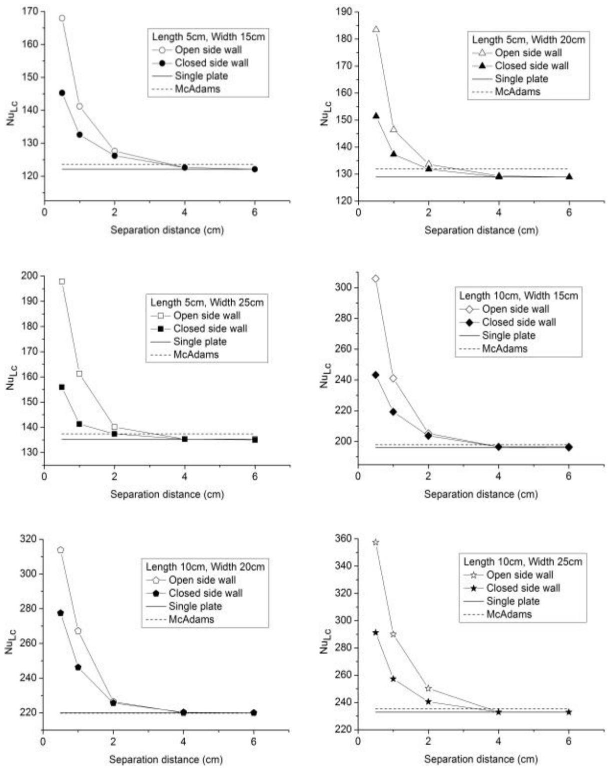


Fig. 4. The effect of varied area of copper plate.

The measured Nu_{Lc}'s show similar trends and they decrease with the plate separation distances. At about 4cm of the separation distances between the lower and the upper plates, the influence of the upper plate disappear. As the area of plate increases, the measured absolute value of the Nu_{Lc}, increases.

The Nu_{Lc}'s measured for closed side walls are less than those for open side walls. The differences of the Nu_{Lc}'s between the open and the closed side walls become clear when the plate separation distances reduce. It can be explained by the circulating flow which causes the inflow of the cold fluid at side while the hot plume was rising [8].

5. Conclusions

The Rayleigh-Benard natural convection were investigated experimentally varying the area of plate and the plate separation distance with/without the side walls. The measured results for a single upward-facing plate were in consistent with the correlation developed by McAdams. It is confirmed that the increase of the area of plate and the decrease of the plate separation distance enhanced the natural convection heat transfer. And the heat transfer rates for open side wall cases were larger than ones for closed side wall cases.

In order to simulate the Rayleigh-Benard problem occurs in the metallic layer of molten pool in the severe accident conditions, further works are undertaken such as material property investigation, scaling analysis, and test design to simulate the irregular crust surface conditions, etc.

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