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Influence of Prandtl Number and Height on Laminar Natural convection in a Rectangular Enclosure

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1. Introduction

During the In-Vessel Retention (IVR) process, the strategy of External Reactor Vessel Cooling (ERVC) is one of the key severe accident management. The molten pool is stratified into two layers by the density difference. 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) [1].

"Rayleigh-Benard natural convection" occurs in the metallic layer. And the heat fluxes were imposed on the side walls. This is called "Focusing effect" [1-3]. The natural convection in a horizontal enclosure such as Rayleigh-Benard convection is affected by the properties of fluid, size of enclosure, cooling conditions and so on [4-7].

In this study, the numerical and experimental works were performed to explore the influence of *Pr* and height on the internal flow and heat transfer in the rectangular enclosure. The numerical study was conducted varying the cooling conditions, *Pr*, and height of enclosure. The height (*H*) of enclosure was varied from 0.005 m to 0.02 m, *Pr* was 0.2, 0.7, 7, and 2,014, which correspond to $2.12\times10^3 \le Ra_H \le 9.85\times10^7$. The numerical calculations were carried out using FLUENT 6.3 [8]. In order to verify the numerical studies, the experiments were performed for a few cases corresponding to numerical simulation. Mass transfer experiments based on the analogy concept were carried out using a copper sulfate-sulfuric acid ($CuSO_4$-H_2SO_4) electroplating system.

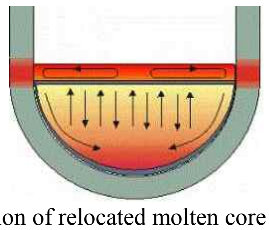


Fig. 1 Distribution of relocated molten core material.

2. Previous studies

2.1 Cell pattern in the enclosure

Most of the natural convection studies regarding the enclosure have been targeting at the unidirectional heat flow, i.e., the buoyancy is induced by imposing a heating either from the side or from the below toward the opposite wall. There are a few studies on the multidirectional heat flow as the internal flow of enclosure is more complex [5, 9, 10].

The bottom and top wall are heated and cooled, respectively. In this situation, Rayleigh-Benard natural convection occurs. The cells are formed by the developed hot and cold plumes from upper and lower walls. These cells are called the Benard cells (Fig. 2) [11, 12].

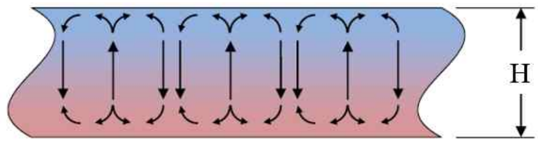


Fig. 2. Flow pattern of Rayleigh-Benard natural convection.

2.2 Natural convection of multidirectional heat flow in the enclosure

Corcione [5] carried out the numerical study to investigate the influence of the thermal boundary conditions at the side walls in the two-dimensional rectangular enclosures heated from the bottom and cooled from the top. Six cases of boundary configurations for the side walls were applied using heating, cooling, and adiabatic conditions. The aspect ratio (*L*/*H*) and Ra_H ranged from 0.66 to 8 and 10^7 to 10^{10}, respectively. He reported that the number of cells for the flow field increases as the aspect ratio (*L*/*H*) increases. In case of cooling condition at side walls, the heat transfer was improved than adiabatic condition of side walls due to direct heat exchange.

Dalal and Das [9] performed the numerical analysis for natural convection in a two-dimensional rectangular enclosure heated from bottom. Other three walls were kept constant at lower temperature than bottom wall. They explained the characteristics of cell pattern for the ranges of $10^0<Ra_H<10^6$, $0.5<L/H<2$. They reported that the mixing of the flow is achieved with increase of Ra_H, as the upward flow caused the buoyance is active. Also, the heat transfer and circulation are enhanced by increase of the cooling area with increase of aspect ratio.

Basak *et al.* [6] carried out the numerical study to confirm the steady laminar natural convection flow in a square cavity heated from bottom. The range of parameters were $10^3<Ra_H<10^5$ and Pr=0.7, 10. They reported that the circulation of flow depends on Rayleigh number in laminar condition. Saha *et al.* [10] carried out the numerical study on natural convection in the two-dimensional rectangular enclosure heated from bottom, cooled from side walls, and insulated at the top. Their results and explanations were similar to these of other scholars.

As the interaction between the boundary layer and the core flow increases for multidirectional heat flow in the enclosure, the instability of the internal flow increases. Despite the importance in the internal multidirectional heat flow of the enclosure, many studies were performed limitedly because the internal flow problems are considerably more complex. Thus, the researches on properties of fluid, height of enclosures and cooling conditions are needed certainly.

3. Numerical analysis

Figure 3 shows the simulation domain, three-dimensional rectangular enclosure. In order to simulate both the unidirectional and multidirectional heat flow, the side wall conditions were either adiabatic or cooled. The heated bottom wall temperature is kept at the constant temperature of 500K. The temperature of top wall is maintained at 300K. And the initial temperature of an interior fluid is 400K.

The numerical analyses were carried out for laminar flow conditions using FLUENT 6.3 [8]. The PRESTO (PREssure Staggering Option) scheme was used, and the second-order upwind algorithm with segregated solver was used for momentum and energy. The SIMPLE (Semi-Implicit Method for the Pressure-Linked Equation) algorithm was used to couple the pressure-velocity fields as it is widely used to solve problems for incompressible flows [9, 13, 14].

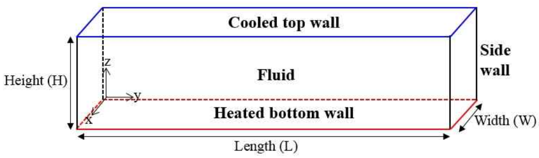


Fig. 3. Simulation domain.

Table 1 shows the test matrix for the numerical simulations. The length (L) and width (W) were fixed to 0.148 m and 0.01m, respectively. The height (H) of enclosure was varied from 0.005 m to 0.04 m and Pr from 0.2 to 2,014, which correspond to Ra_H ranging from 2.12×10^3 to 9.85×10^7.

Table I: Test matrix

Pr	H (m)	L/H	Gr_H	Cooling condition
0.2, 0.7, 7, <u>2,014</u>	<u>0.005</u>, <u>0.01</u>, 0.02, 0.04	29.6, 14.8, 7.4, 3.7	5.27×10^3, 4.21×10^4, 3.37×10^5, 2.70×10^6	Top cooling only, Top and Side cooling

4. Experimental analysis

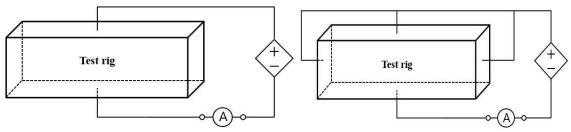
4.1 Analogy concept with the electroplating system

Heat and mass transfer systems are analogous, as the governing equations and parameters are of the same form mathematically [17]. Thus, heat transfer experiments can be replaced by mass transfer experiments.

In this study, a copper sulfate-sulfuric acid ($CuSO_4$-H_2SO_4) electroplating system was used as the mass transfer system. A more detailed description of this methodology can be found in the paper by Park and Chung [18].

4.2 Apparatus and test matrix

The experimental apparatus was equivalent to the simulation domain of numerical analysis in Fig. 3. The schematic circuit is shown in Fig. 4. The copper cathode and copper anode, acted as the heated and cooled walls, respectively. And the acryl front and rear walls are adiabatic. The cases of experiment are the underlined cases (Pr=2,014, H=0.005, 0.01 m) in Table I. Sc was 2,014, which corresponds to Pr.



(a) Top cooling (b) Top and Side cooling

Fig. 4. The schematic circuit.

5. Results and discussion

5.1 Comparison of numerical and experimental results

Figure 5 compares the results of this study with the correlations of the existing studies for the unidirectional heat flow condition such as Rayleigh-Benard convection. Pr=2,014, the open symbols overlap with the closed ones showing that the experimental results agreed well with numerical results and they agreed with the Globe and Dropkin correlation within 5% error. For Pr=0.2, 0.7, 7, the numerical results lie among the existing correlations and show a consistency.

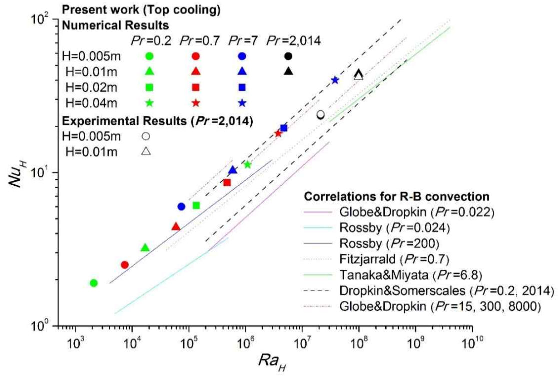
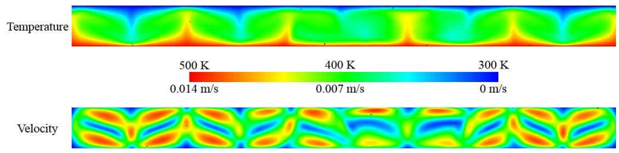


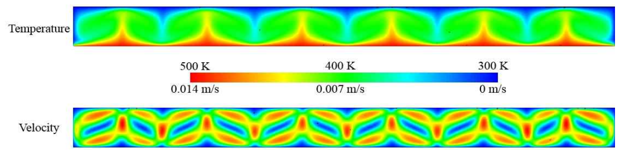
Fig. 5. The comparison of results for top cooling condition.

5.2 The results at different cooling conditions

Figure 6 shows the temperature and velocity contours for *Pr*=0.7, *H*=0.01 m. The red rising plumes and blue descending plumes form rotating flow cells, which match with velocity contours. The flow directions at side walls in Fig. 6(a) and (b) differed due to cooling condition at the side walls. Another difference on the cooling condition is the number of cells. For the top and side cooling condition, the number of cells was larger than those for the top cooling condition. The extra cells at both ends circulating in opposite directions were added due to the added side cooling. Thus, the cells in the enclosure were shifted by the cooling condition at side walls.



(a) Top cooling condition



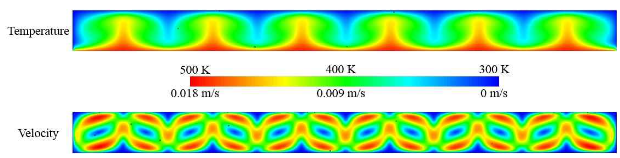
(b) Top and side cooling condition

Fig. 6.Temperature and velocity contours according to the cooling condition for *Pr*=0.7, *H*=0.01 m.

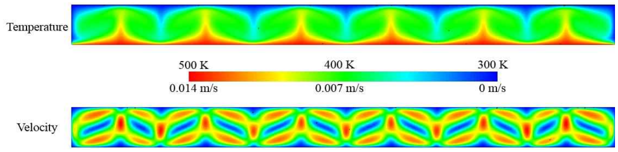
5.3 The influence of Pr for multidirectional heat flow

Figure 7 shows the temperature and velocity contours for *H*=0.01 m at various *Pr*'s for top and side cooling. The thermal plumes for *Pr*<1 were formed thickly as in Fig. 7(a) and (b), whereas they became thinner for *Pr*>1 as shown in Fig. 7(c) and (d) as the relative thicknesses of the thermal boundary layer to the momentum boundary layer varies with *Pr* [11].

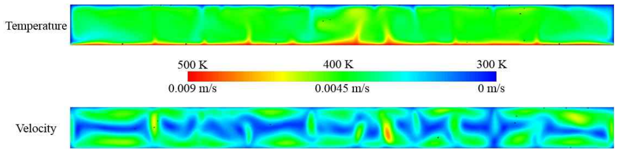
For *Pr*<1, the heat transfer depends more on the thermal diffusion of the fluid. As the buoyancy decreases during the rising of plumes, the thermal plumes did not reach the top wall. For *Pr*>1, the heat is carried more by thermal plumes, they reached the top wall. However, the very thin plumes in Fig. 7(c) and (d) lost directions and became chaotic due to the friction between the plumes and the fluid.



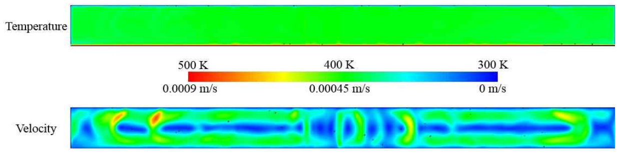
(a) *Pr*=0.2



(b) *Pr*=0.7



(c) *Pr*=7

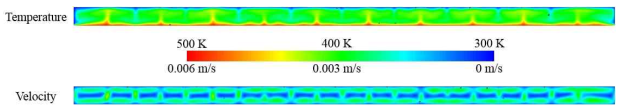


(c) *Pr*=2,014

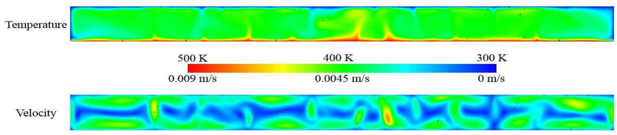
Fig. 7.Temperature and velocity contours according to Prandtl number for *H*=0.01 m.

5.4 The influence of the height for multidirectional heat flow

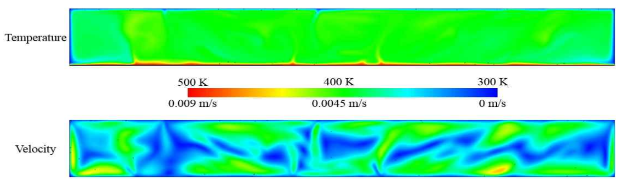
Figure 8 and 9 shows the temperature and velocity contours of various heights (*H*) with *Pr*=7, 0.7 for top and side cooling. In Fig. 8(c), the overall flow was chaotic due to the influence of *Pr*. As the height (*H*) reduced, the cell pattern was observed clearly and the flow became relatively stable.



(a) *H*=0.005 m



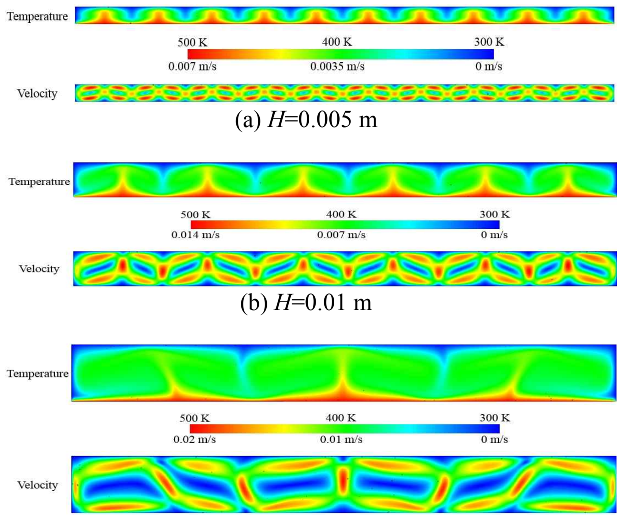
(b) *H*=0.01 m



(c) *H*=0.02 m

Fig. 8. Temperature and velocity contours according to the height (*H*) of enclosure for *Pr*=7.

In Fig. 9, the cell patterns were stably formed for all heights due to *Pr*<1. When the height for a moderated *Pr* decreased, the flow became stable and the number of cells increased. For smaller *Pr*, the flow patterns were stable regardless of height.



(a) *H*=0.005 m

(b) *H*=0.01 m

(c) *H*=0.02 m

Fig. 9. Temperature and velocity contours according to the height (*H*) of enclosure for *Pr*=0.7.

6. Conclusions

The numerical and experimental analyses in the rectangular enclosure were performed to investigate the influence of *Pr* and height (*H*) on the unidirectional and multidirectional heat flow. The numerical analyses were carried out using FLUENT 6.3 for a wide range of *Pr* and *H*. Based on the analogy concept between heat and mass transfer, mass transfer experiments were performed using $CuSO_4$-H_2SO_4 electroplating system.

For bottom heating and top cooling condition that simulated the unidirectional heat flow, the numerical and experimental results agreed with the existing correlations for Rayleigh-Benard convection with the error of 5%. For top and side cooling condition, the results of this work showed the similar trend with the existing studies.

When the height decreased, the number of cells increased and the heat transfer in the enclosure increased. For *Pr*<1, due to the thicker thermal plumes the cell patterns were formed regularly and stably. But for *Pr*>1, the thinner plumes were formed and moved randomly due to the interaction between these plumes and the fluid. Therefore the flow become chaotic for the lowest height (*H*).

This study analyzed the influences of the cooling condition, height (*H*) and *Pr* on the internal flow. Besides those, other parameters important to the internal flow such as the geometry of enclosure, dimension, various temperature conditions, etc. The researches for these parameters in the enclosure are needed.

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