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The Numerical Study on the Influence of Prandtl Number and Height of the Enclosure

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1. Introduction

In-Vessel Retention - External Reactor Vessel Cooling (IVR-ERVC) of core melt is one of the key severe accident management strategies. The molten pool is stratified into two layers by the density difference. The metallic layer is heated from below by the 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].

This study investigated numerically the internal flow depending on Prandtl number of fluid and height of enclosure. The two-dimensional numerical simulations were performed for several heights of enclosure in the range between 0.01 m and 0.074 m. It corresponds to the aspect ratio (H/L) ranged from 0.07 to 0.5. Prandtl number was 0.2, 0.7 and 7. Rayleigh number based on the height of enclosure ranged between 8.49×10^3 and 1.20×10^8. The numerical calculations were carried out using FLUENT 6.3 [8].

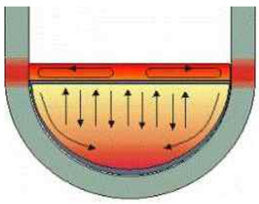


Fig. 1 Distribution of relocated molten core material.

2. Previous studies

The bottom and top wall are heated and cooled, respectively. And the side walls are adiabatic. 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 or Benard pattern (Fig. 2) [9, 10]. When the side walls are cooled, the internal flow of enclosure is more complex.

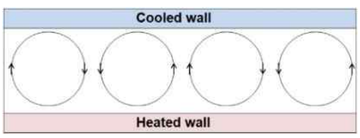


Fig. 2. Flow pattern of Rayleigh-Benard natural convection.

The natural convection in horizontal enclosures has been extensively studied both experimentally and numerically. Horvat and Kljenak [4] carried out the numerical study on the cell formation with the Ra=10^6 ~10^{13} and Pr=0.8. For laminar flow (Ra_H<10^8), the cells were formed stable and regular, while for turbulent flow (Ra_H >10^8), the cells became unstable due to an oscillation of fluid. Massimo Corcione [5] investigated the effects of the thermal boundary conditions in the rectangular enclosures numerically. The Rayleigh number and aspect ratio (L/H) ranged from 10^3 to 10^6 and 0.66 to 8, 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. T. Basak et al. [6] carried out the numerical study to confirm the steady laminar natural convection flow in a square cavity heated bottom wall. The Rayleigh number and Prandtl number ranged from 10^3 to 10^5 and 0.7 to 10, respectively. They reported that the circulation of flow depends on Rayleigh number in laminar condition.

Despite the importance in the internal flow of the enclosure, many studies were performed limitedly. As the internal flow problems are considerably more complex, the researches on properties of fluid, height of enclosures are needed certainly.

3. Numerical analysis

Figure 3 shows the simulation domain, indicating the boundary conditions and coordinates. The heated bottom wall temperature is kept at the constant temperature of 400K. The temperature of top and side wall is maintained at 200K. And the initial temperature of an interior fluid is 300K

The test matrix shown in Table I. The length (L) is fixed to 0.148m. In order to include the aspect ratio (H/L) range of molten pool and existing studies, the height (H) of enclosure ranged from 0.01m to 0.074m. For a similar reason, Prandtl number is varied between 0.2 and 7.

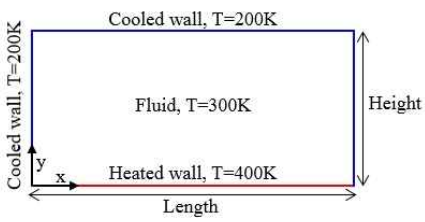


Fig. 3. Simulation domain.

Table I: Test matrix

Pr	**L(m)**	***H*(m)**	***Gr_H***	**Cooling condition**
7	0.148	0.01, 0.02, 0.04, 0.074	4.21×10^4, 3.37×10^5, 2.70×10^6, 1.71×10^7	Top cooling only, Top+Side cooling
0.7				Top+Side cooling
0.2				

In order to investigate the detailed cell behaviors according to Prandtl number and height of enclosure, a numerical study was carried out using the commercial CFD program FLUENT 6.3 [8]. The calculations were conducted laminar flow conditions. A second order upwind algorithm was used for laminar flow conditions, where the SIMPLE algorithm was used to couple the pressure-velocity fields.

4. Results and Discussion

Figure 4 shows the comparison of the numerical results with the existing Rayleigh-Benard natural convection correlations. The top wall is cooled and side walls are adiabatic. The numerical results agree well with the heat transfer correlations [11].

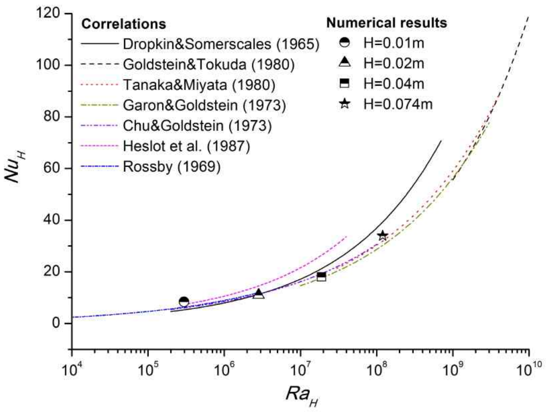
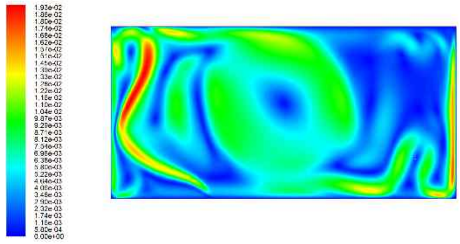
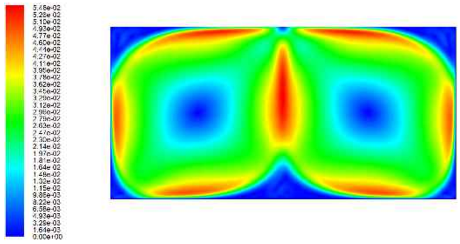


Fig. 4. The comparison of the results with the Rayleigh-Benard natural convection heat transfer correlations.

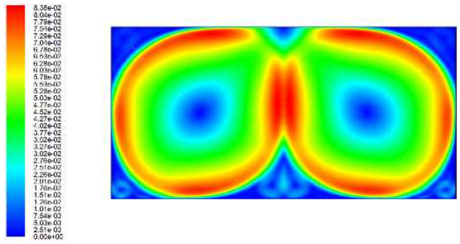
Figure 5 presents the velocity contours according to Prandtl number for H=0.074 m. The top and side walls are cooled at constant temperature. For $Pr>1$, the thickness of a thermal boundary layer is thinner than the velocity boundary layer. The fluid motion is not restricted to the thermal boundary layer. It is possible for a heated layer to entrain viscously the unheated layer [9]. Thus, in Fig. 5(a), the internal flow is unstable and cells were twisted. For $Pr<1$, the thermal boundary layer thickness is thinker than the velocity boundary layer. The flow was driven by the buoyancy. The formation of cells was regular and stable as shown in Fig. 5(b) and (c).



(a) Pr=7



(b) *Pr*=0.7

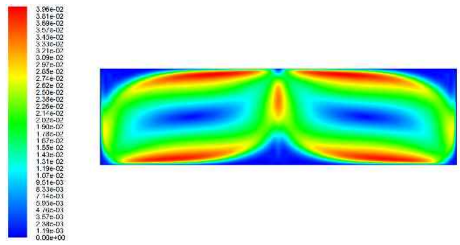


(c) *Pr*=0.2

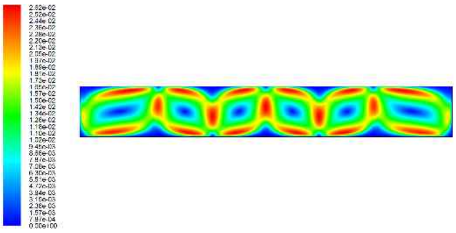
Fig. 5. The velocity contours according to Prandtl number for H=0.074m.

Figure 6 shows the velocity contours according to height of enclosure with *Pr*=0.7. When the side walls are cooled, the downward cold plume moves toward the center of bottom wall. And then it pushes the hot plume toward top wall. The cold plume of top wall moves toward side walls. Finally, the cells are formed. When the height of enclosure decreases, the portion of downward cold plume of side walls decreases. The cold plume does not reach the center of bottom wall. Thus cells were formed early at the side walls, and then spread to the whole enclosure. Thus, the formation time and size of cells is influenced by the height of side wall.

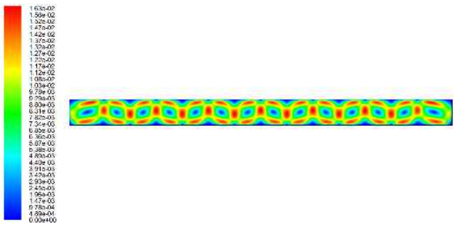
Also, for shorter height of enclosure, the heat transfer was enhanced by the active interaction between hot and cold plume. As the number of cells increases, the heat exchange increases.



(a) H=0.04m



(b) H=0.02m



(c) H=0.01m

Fig. 6. The velocity contours according to height for *Pr*=0.7.

5. Conclusions

In order to confirm the influence of Prandtl number and height of side walls on the internal flow and heat transfer of the horizontal enclosure, the numerical study is carried out using the FLUENT 6.3.

The numerical results for the condition of top cooling only agree well with Rayleigh-Benard natural convection. When the top and side walls were cooled, the internal flow of enclosure is more complex. The thickness of thermal and velocity boundary layer varies with Prandtl number. For $Pr>1$ the behavior of cells is unstable and irregular owing to the entrained plume, whereas the internal flow for $Pr<1$ is stable and regular. Also, the number of cells increases depending on decrease of height. As a result, the heat exchange increases.

The internal flow of metallic layer is affected the heating condition of lower oxide pool, the cooling condition of top and side walls, the properties, height of metallic layer, etc. In order to predict heat flux at the side walls, this work will investigate the real properties of molten pool and input the data to calculations.

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REFERENCES

[1] T. G. Theofanous et al., In-vessel coolability and retention of a core melt, Nuclear Engineering and Design, Vol. 169, pp. 1-48, 1997.
[2] J. L. Rempe et al., In-vessel Retention of Molten Corium: Lessons Learned and Outstanding Issues, Nuclear Technology, Vol. 161, pp. 210-267, 2008.
[3] C. Liu, T. G. Theofanous, The MELAD experiment, Department of Chemical and Nuclear Engineering, University of California, Santa Barbara, 1996.
[4] Andrej Horvat, Ivo Kljenak, Dynamics behavior of the melt pool at severe accident conditions, (NURETH-9) San Francisco, California, 1999.
[5] Massimo Corcione, Effects of the thermal boundary conditions at the sidewalls upon natural convection in rectangular enclosures heated from below and cooled from above, International Journal of Thermal Sciences, Vol. 42, pp. 199-208, 2003.
[6] T. Basak, S. Roy, A.R. Balakrishnan, Effects of thermal boundary conditions on natural convection flows within a square cavity, International Journal of Heat and Mass Transfer, Vol. 49, pp. 4525-4535, 2006.
[7] Leo P. Kadanoff, Turbulent Heat Flow: Structures and Scaling, Physics Today, pp. 34-39, 2001.
[8] Fluent User's Guide release 6.3 Fluent Incorporated, 2006.
[9] Adrian Bejan, Convection Heat Transfer 4th Edition, pp. 262-266, pp. 176-180, 2013.
[10] Jean Hertzberg, Two visualizations of Rayleigh-Benard convection cells, 2010.
[11] R.J. Goldstein, H.D. Chiang, D.L. See, High Rayleigh number convection in a horizontal enclosure, Journal of Fluid Mechanics, Vol. 213, pp. 111-126, 1990.