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Rayleigh-Benard Natural Convection Cell Formation and Nusselt number

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1. Introduction

The molten pool is formed in a hypothetical severe accident condition at the lower head of reactor vessel and is stratified into two layers by the density difference: an upper metallic layer and a lower oxide pool. Rayleigh-Benard natural convection occurs in the metallic layer of relocated molten pool [1].

This study aimed at the investigation of the time-dependent cell formation and Nusselt number variation in Rayleigh-Benard natural convection. Time dependent variation of Nusselt number was also measured experimentally and analyzed numerically to investigate the relationship between the cell formation and Nusselt number.

Based on the analogy, heat transfer experiments were replaced by mass transfer experiments using a sulfuric acid-copper sulfate (H_2SO_4-$CuSO_4$) electroplating system. Numerical analysis using the commercial CFD program FLUENT 6.3 were carried out with the same material properties and heating conditions to examine the variation of the cell, the formation time.

2. Previous studies

The Rayleigh-Benard natural convection is affected by the separation distance between the horizontal plates [2]. When Rayleigh-Benard natural convection occurs, cells are formed by developed plumes from upper and lower plates. These cells are called the Benard cells or Benard pattern (Fig. 1) [3, 4].

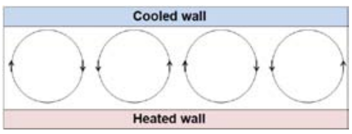

Fig. 1. Flow pattern of Rayleigh-Benard natural convection.

An explanation on the cell formation process is tried by many scholars [5-8]. Horvat and Kljenak [8] carried out the numerical study on the cell formation for the Rayleigh range between 10^6 and 10^{13}. For laminar ($Ra_s<10^8$), the cells were formed stably and regularly, while for turbulent ($Ra_s >10^8$), the cells became unstable. Dinh et al. [6] investigated the onset and the pattern formation of the cell with time, using the water as the working fluid, varying the heat flux. They showed that the time is 10s. Xi et al. [7] carried out an experimental study on the cell of the Rayleigh-Benard natural convection for Rayleigh number 6.8×10^8 and Prandtl number 596. They reported that the cell formation time was 2,640s (44min).

The numerical and experimental results of the existing studies regarding the cell formation, growth, superposition, and chaotic behavior are similar but the timings do not agree.

3. Experiments

3.1 Experimental apparatus

The experimental apparatus consisted of an upward-facing copper cathode plate, a downward-facing copper anode plate and acrylic supports (Fig. 2).

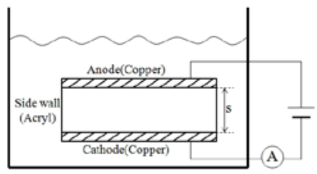

Fig. 2. The experimental apparatus.

Table I: Test matrix.

Length (m)	Width (m)	Separation distance (m)	Ra_s
0.05, 0.1	0.15, 0.2, 0.25	0.005	1.06×10^7
		0.01	8.49×10^7
		0.02	6.79×10^8
		0.04	5.43×10^9
		0.06	1.83×10^{10}

The test matrix shown in Table I. The Rayleigh number ranged from 1.06×10^7 to 1.83×10^{10} and Prandtl number was 2,014.

In order to achieve high Rayleigh numbers, the heat transfer experiments were replaced by mass transfer experiments based on the analogy concept. A sulfuric acid-copper sulfate (H_2SO_4-$CuSO_4$) electroplating system was adopted as the mass transfer system.

3.2 Numerical analysis

In order to confirm the cell formation with time, a numerical study was carried out using the commercial CFD program FLUENT 6.3 [9]. The simulations were carried out using the Boussinesq approximation, and the temperature of the heated wall, the cooled wall, and an interior fluid was maintained at 400 *K*, 200 *K*, and 300 *K*, respectively. The test matrix for the experimental study is presented in Table 1. The numerical study is also performed for the underlined cases.

4. Results and discussion

Figure 3 compares the current experimental results with the existing heat transfer correlations. The experimental results agree well with the heat transfer correlations of Dropkin and Somerscale [10] and Globe and Dropkin [11] with *Pr* =8,000.

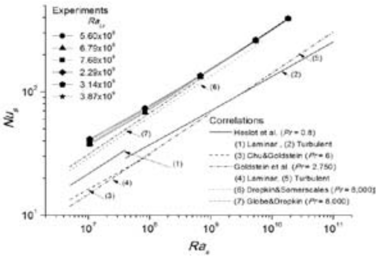

Fig. 3. The comparison of the test results with the Rayleigh-Benard natural convection heat transfer correlations.

Figure 4 shows the measured and calculated time dependent variation Nu_s and the images of the velocity field, showing the cell formation and growth when the separation distance is 0.004m. At around 45s, the Nu_s show the minimum value, when the heated plumes starts to be generated at the lower plate and they move straight upward without any visible wavy-like motion. This signifies the onset of the convection at the lowest Nu_s. Then the Nu_s increases to the peak value at 68s, when the hot and cold plumes developed from the lower plate and upper plates meet. At 76s, the plumes are mixed perfectly and at 85s, the initial square cell is formed. At 120s, the cells merge to a bigger cell and then the chaotic behaviors are observed. After 120s, the Nu_s is nearly constant and the Nu_s is not affected much by the variation of cell pattern.

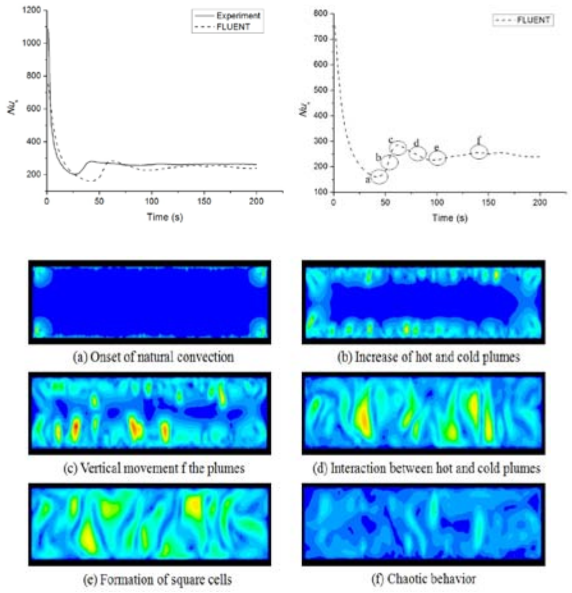

Fig. 4. The time dependent cell formation, growth, and Nusselt number.

5. Conclusions

The experimental and numerical studies for were performed to investigate time-dependent cell formation and Nusselt number variation in Rayleigh-Benard convection as a fundamental study.

The experimental results lie within the predictions of the existing heat transfer correlations for the Rayleigh-Benard natural convections even though the material properties were different. For shorter separation distances, the heat transfers enhance due to the active interaction between heated and cooled plumes.

For a step temperature difference, the time dependent Nusselt number variations were investigated. Both experimental and numerical results showed that with time the Nusselt number decreases monotonically to a minimum point presenting the onset of convection. As the hot and cold plumes increase and convey the heat to the other plates, the Nusselt number increases to the local maximum point, presenting the vertical movements of the plumes. Then, the Nusselt number fluctuates with the formation of square cells and larger vortices. This also predicted by the mass transfer experiment.

The experiments and calculations show similar trend but the timings were different. These discrepancies are caused by the disturbances inherent in both systems.

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