Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 8-10, 2024

Natural convection at high Rayleigh number with mass transfer experiment

Dong-Gyu Lee, Seong-Il Baek and Bum-Jin Chung*
Department of Nuclear Engineering, Kyung Hee University
#1732 Deogyeong-daero, Giheung-gu, Yongin-si, Gyeonggi-do, 17104, Korea
**Corresponding author*: *bjchung@khu.ac.kr*

Keywords : Natural convection, High Rayleigh, mass transfer

1. Introduction

Recently, SMR market is extended and most of pressurized water SMR receive attention especially. The most of pressurized water SMR deal with loss of coolant accident (LOCA) employing PCCS (Passive Containment Cooling System). SMRs use PCCS to remove heat from metal containment vessels, but some of them has finite operation time. So the heated surface of steel containment encountered in the accident has Rayleigh number higher than 10^{15} at air condition. In SMR regulation point of view, there is only a few correlations of natural convection extending $Ra_H = 10^{15}$. From the perspective of SMR regulation, there are only a few correlations for natural convection under conditions where Rayleigh number exceeds 10^{15}. So, demands of knowledge about correlation and heat transfer behavior where Rayleigh number exceeds 10^{15} are growing.

FOUAD and IBL developed a natural convection correlation where Ra_H extends up to 10^{15} by employing mass transfer experiments [1]. They measured average Nu_H but did not check transition point of laminar to turbulent. Fujii et al. measured turbulent natural convection at a vertical cylinder using various fluid [2]. A piecewise vertical cylinder is applied to measure the local heat transfer rate under both isothermal and isothermal flux conditions. They mentioned the analogy between a vertical plate and a cylinder when the boundary layer is sufficiently thin compared to the diameter of the cylinder. The local heat transfer rate is measured up to $Ra_H = 10^{14}$, and the laminar transition point is confirmed at $Ra_H = 10^{10}$. However, the characteristic of the bulk fluid was not well maintained in the test conditions, since the reservoir enclosing the working fluid and vertical cylinder is not sufficiently large. Vlite and Liu pointed out the reliability of the Fujii et al.'s experimental results due to changes in the bulk fluid [3]. Bejan and Lage questioned the non-dimensional number as the transition point of existing studies [4]. The author noted that Ra_H is not exactly the governing parameter of laminar transition in most of the existing studies. Especially, the experimental study demonstrated that the doubt is correct, employing very low and high Prandtl fluids such as liquid metal and oil [2,5]. They investigated and predicted the laminar transient point, which is $Gr_H = 10^9$, by gathering experimental results from another author. Ko et al. measured laminar and turbulent heat transfer rate using mass transfer electroplating method [6]. They developed laminar and turbulent correlations; the critical transition point was $Gr_H = 5\times10^9$. Their study once again verified Bejan and Lage's consideration on the governing parameter of the transition point.

Various studies on turbulent natural convection at vertical plate under isothermal flux conditions were conducted by many researcher [3,7,8]. These studies differed in the definition of Grashoff number under isothermal and isothermal conditions. This means that even with natural convection heat transfer near the same vertical plate, the heat transfer phenomenon varies depending on the boundary conditions. Additionally, Yang collected laminar, transition, and turbulent correlation equations based on existing studies and presented the critical point of transition of each flow regime [9]. However, the correlation equation in Yang represents average heat transfer, and the boundary conditions (isothermal and isothermal flux) are not distinguished.

In general, few experimental heat transfer research on High Rayleigh condition has been performed due to limitations such as the classification of boundary conditions, large devices for natural convection, and bulk fluid characteristics. However, for efficient SMR licensing, it is important to understand the heat transfer phenomenon within the vertical plate at High Rayleigh condition. By using a mass transfer technique based on analogy between mass and heat transfer, High Rayleigh conditions can be developed efficiently, and high buoyancy can be achieved with a small device. High measurement accuracy can be obtained by current without heat leakage or radiative heat transfer [10]. Especially, since there is no heat conduction loss between local heat transfer measurement devices, accurate local heat transfer measurement is possible. The bulk fluid properties of the mass transfer system are not sensitive to changes in the surrounding environment, making it easy to maintain the fluid properties during the experiment and quickly reach a steady state.

In this study, the local heat transfer on the vertical plate for High Rayleigh was investigated using the copper sulfate-sulfuric acid ($CuSO_4$-H_2SO_4) electroplating technique in the mass transfer system. Additionally, the local heat transfer rate was measured by splitting the plate piecewise, and the flow regime was observed for each height. The height of the plate is 2.0 m, and the corresponding Ra_H and Gr_H are 1.34×10^{15} and 6.43×10^{11}, respectively.

2. Experimental setup

2.1 Methodology

Heat and mass transfer systems are analogous, as the governing equations for the two phenomena are identical [11]. Therefore, by employing the analogy concept, heat transfer experiments can be conducted as mass transfer experiments [12].
In this study, a copper sulfate-sulfuric acid ($CuSO_4$-H_2SO_4) electroplating system served as the basis for the mass transfer experiments.
When electric potential is applied at electrode, cupric ions which released at anode are plated at cathode. As the reaction progress, concentration of cupric ions near the cathode decreases. The difference of cupric concentration induce buoyancy and generate natural convective upward flow at near the cathode by mass transfer. As the amount of copper ions plated on the cathode per second increases, the buoyancy increases. The amount of copper ions exchanged is similar to the amount of heat exchanged, and the amount of copper ions exchanged per unit area (current density) is analogous to the heat flux. To address the challenge of measuring the ion concentration at the cathode surface, a limiting current technique was employed. The physical properties were calculated using the correlation conducted by Fenech and Tobias [13], and the mass transfer coefficient (h_m) followed as:

$$h_m = \frac{(1-t_n)I_{lim}}{nFC_b} \quad (1)$$

More details of this technique can be found in the work of Chung et al., where the technique has been applied in various applications [14,15].

2.2 Test matrix and apparatus

Table 1 shows the test matrix for heat transfer in the vertical plate. The concentration of $CuSO_4$ was 0.1 M and the concentration of H_2SO_4 was 1.5 M. The *Sc* corresponds to *Pr* was 2,093. The height of plate was 2 m, which corresponds to Ra_H of 1.34×10^{15} or Gr_H of 1.34×10^{11}.

Table I: Test matrix for heat transfer in vertical plate

Pr	H (m)	Ra_H	Gr_H
2,093	2.0	1.34×10^{15}	6.43×10^{11}

Figure 1 shows the electric circuit which consisted of the cathode plate, anode, power supply and data acquisition (DAQ) system. The heating plate was submerged in the top-opened acryl tank (*W* 135 mm × *L* 430 mm × *H* 2400 mm) filled with the copper sulfate-sulfuric acid ($CuSO_4$ - H_2SO_4) solution. To measure the local heat transfer on the vertical plate, the cathode was installed in segments, and the contact regions between the segments were insulated. The copper anode was located at the corner of the tank away from the cathode to minimize the effect of the anode position. The electric voltage was controlled using the power supply (Keysight N8952a) and the electric current was measured using the DAQ system (NI 9227).

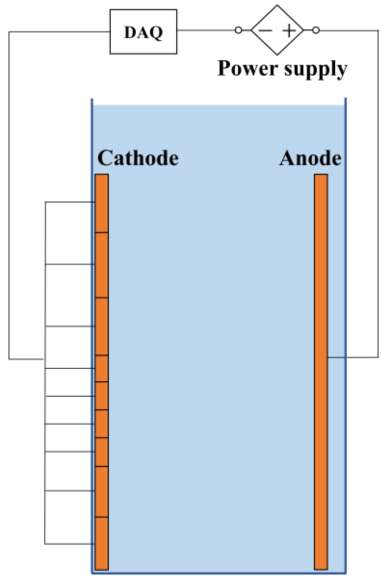
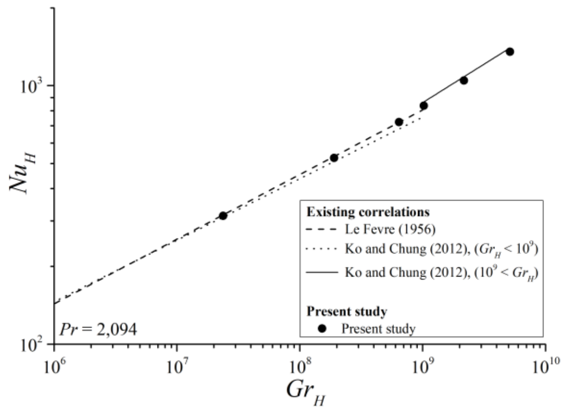


Fig. 1. Schematic circuit for experimental apparatus.

4. Results and discussion

4.1 Comparison results with existing correlation for vertical plate

Figure 2 is a graph comparing the existing correlation and the present results. Many existing research have mentioned that the transition on vertical plate natural convection is dominated by the dimensionless number Gr_H. Therefore, in this study, Gr_H was used instead of Ra_H for the Nu graph to confirm the flow transition. Each point on the graph is the average Nusselt value. The correlation used for comparison also represents the average Nusselt under isothermal conditions. The maximum relative error was 6.2%, which was good



agreement with the results of existing studies.

Fig. 2. Comparison results with existing correlation.

4.2 Local heat transfer rate with confirming laminar transient point

Figure 3 shows the current density measured at each cathode. The horizontal axis of the graph represents the cathode number, and the vertical axis represents the current density. As the number of cathodes increases, the cathode height increases, and Gr_H increases accordingly. cathodes 1, 15, and 25 are located at heights corresponding to $Gr_H = 2.4\times10^7$, $Gr_H = 5.1\times10^9$, and $Gr_H = 2.9\times10^{10}$, respectively. The measured current density corresponds to the heat flux in the heat transfer experiment. Under isothermal conditions, the thickness of the laminar boundary layer increases as the height of the vertical wall increases. The thick laminar boundary layer reduces the current density as Gr_H increases. As the transition begins, the laminar boundary layer becomes unstable and the boundary layer near the vertical walls becomes partially thin. The thinned boundary layer causes a rapid increase in current density. After the transition, the velocity and thermal boundary layers thicken again and the current density decreases slightly. The results of this experiment confirmed the laminar flow transition point $Gr_H = 5.0\times10^9$.

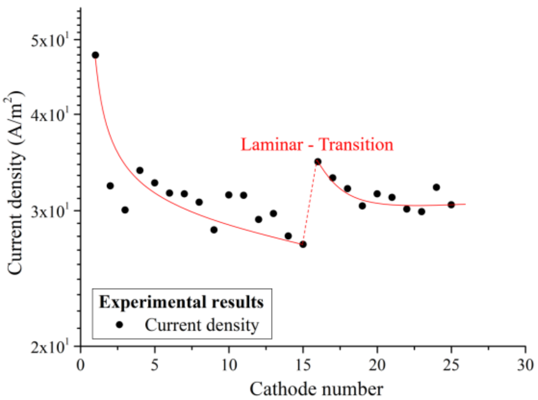


Fig. 3. Current density with laminar transition point.

Figure 4 is a graph about local Nu_H according to local Gr_H. Local Gr_H was obtained based on the top height of each cathode, and local Nu_H was evaluated from the current density of that cathode. The hollow dots represent the local Nu_H of each cathode. The laminar transition point identified from the change in current density along the electrode was observed at a similar Gr_H. In addition, the point where the transition region changes into a turbulent flow region was observed around $Gr_H = 2\times10^{10}$. The change rate of local Nu_H near the transition region is greater than the increase rate in laminar and turbulent flows, which shows a similar trend to previous studies [2,3].

The exponents for Gr_H in the laminar, transitional, and turbulent flow region correlation equations developed in this study are 0.25, 0.38, and 0.33, respectively. This study confirmed the local Nu_H up to $Gr_H = 6.43\times10^{11}$, and the Ra_H for that Gr_H is 1.35×10^{15}.

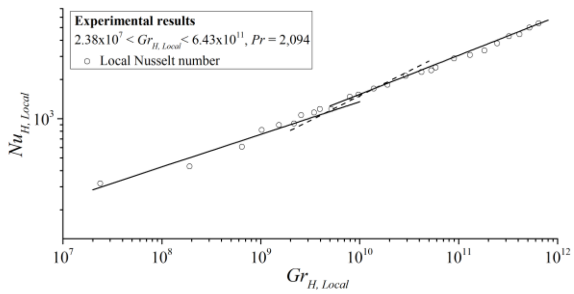


Fig. 4. Local Nu_H with varying local Gr_H.

5. Conclusions

This study measured turbulent natural convection at High Rayleigh employing an electroplating method based on the analogy between mass transfer and heat transfer. To observe flow regime at different heights, cathodes were made piecewise and local heat transfer was measured. The average Nu_H was calculated using piecewise cathodes and compared with the existing correlation, and it agreed well. The local heat transfer measurements in this study were expressed with current density and local Nu. It was confirmed that the laminar flow transition point appears around $Gr_H = 5\times10^9$. A turbulent transition was observed around $Gr_H = 2\times10^{10}$, and then turbulent heat transfer developed well. In the further studies, we plan to investigate the instability of natural convection on a vertical plate and perform a more detailed analysis of the flow regime using the Particle Image velocimetry (PIV) flow visualization method.

ACKNOWLEDGEMENT

This work was also supported by the Human Resources Development of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Knowledge Economy (No. RS-2023-00244330).

REFERENCES

[1] FOUAD, M. G., IBL, N. Natural convection mass transfer at vertical electrodes under turbulent flow conditions. *Electrochimica Acta*, 3.3: 233-243, 1960.

[2] Fujii, T., Takeuchi, M., Fujii, M., Suzaki, K., & Uehara, H. Experiments on natural-convection heat transfer from the outer surface of a vertical cylinder to liquids. *International Journal of Heat and Mass Transfer*, 13.5: 753-787, 1970.

[3] Vliet, G. C., and Liu, C. K. An experimental study of turbulent natural convection boundary layers. 517-531, 1969.

[4] Bejan, A., Lage, J. L. The Prandtl number effect on the transition in natural convection along a vertical surface. *Journal of heat transfer*, *112*(3), 787-790, 1990.

[5] Uotani, M. Natural convection heat transfer in thermally stratified liquid metal. *Journal of Nuclear Science and Technology*, *24*(6), 442-451, 1987.

[6] Ko, B. J., Kim, M. H., Chung, B. J. An experimental study on the transition criteria of open channel natural convection flows. *Journal of mechanical science and technology*, *26*, 1227-1234, 2012.

[7] Godaux, F., Gebhart, B. An experimental study of the transition of natural convection flow adjacent to a vertical surface. *International Journal of Heat and Mass Transfer*, *17*(1), 93-107, 1974.

[8] Mahajan, R. L., Gebhart, B. An experimental determination of transition limits in a vertical natural convection flow adjacent to a surface. *Journal of Fluid Mechanics*, *91*(1), 131-154, 1979.

[9] Yang, S. M. Improvement of the basic correlating equations and transition criteria of natural convection heat transfer. *Heat Transfer—Asian Research: Co-sponsored by the Society of Chemical Engineers of Japan and the Heat Transfer Division of ASME*, *30*(4), 293-300, 2001.

[10] S.I. Baek, J.Y. Moon, B.J. Chung, Natural convective heat transfer influence between two spheres in a packed bed, Int. Commun. Heat Mass Transf. 139 (2022) 106430.

[11] A. Bejan, Convection heat transfer, 4th ed., Wiley, New York, pp. 489–517, 2013.

[12] S.H. Ko, D.W. Moon, B.J. Chung, Applications of electroplating method for heat transfer studies using analogy concept, Nuclear Engineering and Technology, Vol. 38, pp. 251-258, 2006.

[13] E.J. Fenech, C.W. Tovias, Mass transfer by free convection at horizontal electrodes, Electrochim Acta, Vol. 2, pp. 311–325, 1960.

[14] J.W. Bae, B.J. Chung, Comparisons of 2–D and 3–D IVR experiments for oxide layer in the three–layer configuration, Nuclear Engineering and Technology, Vol. 52, pp. 2499–2510, 2020.

[15] D.H. Shin, H.K. Park, B.J. Chung, Measurements of natural convection heat transfer of a helical coil varying the pitch and the turn, Exp. Therm. Fluid Sci. 146 (2023) 110921.