Transactions of the Korean Nuclear Society Spring Meeting
Gyeongju, Korea, May 29-30, 2008

An Experimental Study on the Transition Criteria of Natural Convective Flows

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1. Introduction

The criteria for the transition of the forced convection flows from laminar to turbulent are universally agreed. However, those for the transition of the natural convection flows are not clear: Some use Ra for the criteria while others use Gr.

For the conventional fluids such as air and water, the values of Pr number range from 0.7 to 7. Thus there are at best an order difference between Ra and Gr. However for the fluids of very high or low Pr number, there are large differences between Ra and Gr values.

This study sought the proper governing parameter of the transition criteria for the natural convection flows. In order to obtain high Ra and/or Gr values, the analogy concept is employed. Using the electroplating system as the mass transfer system simulating heat transfer system, Ra value of 9×10^{12} was obtained with facility height of 0.48 m, which could be achieved with test rigs taller than 10 m with air.

2. Background

Incropera and DeWitt [1] argued that the transition occurs at Ra of 10^9 but Bejan and Kraus [2] at Gr of 10^9. Lots of researches with various Pr numbers, were reported regarding the issue.

For lower values of Pr numbers, Lykoudis used mercury and found that the transition occurs at Ra of 10^7. Mahajan and Gebhart tested with air and reported that the transition occurs at Ra of 2.1×10^8. Grodaux and Gebhart used water and concluded Ra of 3.4×10^9.

For higher values of Pr numbers, Fujii found the transition criteria of Ra = 8.5×10^9 using ethylene glycol (Pr = 28 ~ 30). Touloukian et al. with ethylene glycol (Pr = 40) reported that the transition criteria begins at Ra of 4×10^{10}. Farmer and McKie with a higher Pr fluid (about 200) showed that the laminar flow existed even in range of Ra $10^8 \sim 2.2\times10^{10}$ [3].

3. Experiments

3.1 Experimental Methodology

High Ra and/or Gr values are to be obtained to investigate the natural convection transition criteria. This study used the analogy concept to avoid tall and expensive experimental facilities. Using the analogy concept, heat transfer systems were simulated by mass transfer systems, which could achieve large Ra and/or Gr with reasonable test facility heights.

A copper electroplating system was employed as the mass transfer system. It is an electrolytic cell filled with electrolyte solution of $CuSO_4$ and H_2SO_4. When electric potential is applied to the copper electrodes submerged in the solution, cupric ions are generated from the anode and move to the cathode. The flux of copper ions simulates the heat flux and the cathode represents the heated wall so that the reduction of cupric ions on the cathode results in buoyancy force.

The idea of using electrochemical system to heat transfer problems was pointed out by Agar [4, 5]. And Levich, Selman and Tobias further developed the theory [6, 7]. Chung et al. [8] applied the methodology to the typical heat transfer problems of laminar forced convection and laminar/turbulent natural convection problems and showed the usefulness of the methodology. A more detailed description of the methodology can be found in the paper by Chung et al. [8].

3.2 Facility and Test Matrix

Figure 1 shows the experimental rig and system circuit. The test section is a rectangular tank of 0.12 m$\times$0.35 m$\times$0.55 m, which is made of acryl. The anode and cathode are copper plates of width 0.12 m and height 0.5 m at both sides of the rectangular tank. The tank was filled with electrolyte solution of 0.05 M $CuSO_4$ and 1.5 M H_2SO_4. The Sc number, which corresponds to the Pr number in heat transfer system, is 2,013. The large value of Sc in this system reveals the difference between Ra and/or Gr clearly.

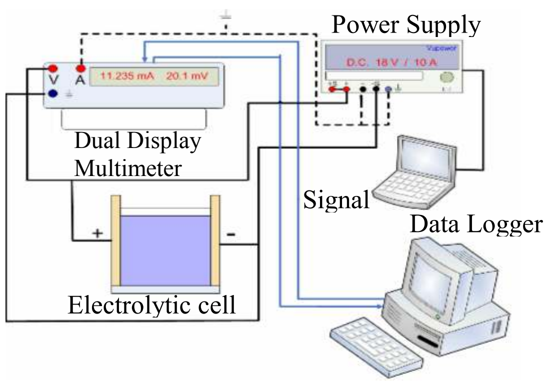

Fig. 1. The experimental equipments and system circuit.

The electric potential was applied by the power supply (*Vü*POWER IPS18B10) and the electric current was measured by the Dual Display Multimeter (FLUKE-45).

The test matrix is shown in Table I. It shows the variations of Ra and Gr depending on the heights of the electrodes. With the electrode height of 0.03 m, 10^9 of Ra is achieved and with the electrode height of 0.3 m, 10^9 of Gr is achieved.

Table I: Test matrix

Height (m)	Ra	Gr	Height (m)	Ra	Gr
0.01	8.4E+07	4.2E+04	0.2	6.7E+11	3.3E+08
0.02	6.7E+08	3.3E+05	0.3	2.2E+12	1.1E+09
0.03	2.2E+09	1.1E+06	0.32	2.7E+12	1.3E+09
0.04	5.4E+09	2.6E+06	0.34	3.3E+12	1.6E+09
0.06	1.8E+10	9.1E+06	0.36	3.9E+12	1.9E+09
0.075	3.5E+10	1.7E+07	0.38	4.6E+12	2.3E+09
0.08	4.3E+10	2.1E+07	0.4	5.0E+12	2.5E+09
0.1	8.4E+10	4.2E+07	0.42	6.2E+12	3.1E+09
0.12	1.4E+11	7.2E+07	0.45	7.7E+12	3.8E+09
0.15	2.8E+11	1.4E+08	0.48	9.3E+12	4.6E+09

3.3 Measurements

The heat transfer correlations for both laminar and turbulent natural convections are known. Using the analogy, those correlations can be transformed to mass transfer correlations by replacing Nu with Sh, and Pr with Sc; [1, 5]

Laminar $Sh_H = 0.59(GrSc)^{1/4}$ at $Gr < 10^9$ (1)

Turbulent $Sh_H = 0.31(GrSc)^{0.28}$ at $Gr \geq 10^9$. (2)

For each electrode height, the limiting current was measured. The limiting current is the current plateau in the applied potential vs. current curve, formed due to the limitation of mass transfer. Thus the mass transfer coefficient is expressed in terms of the limiting current density [5].

4. Results and Discussions

Figure 2 shows the measured mass transfer coefficients together with the known mass transfer correlations, which were transformed from known heat transfer correlations for both laminar and turbulent natural convections.

The dashed and solid lines show the mass transfer correlations for laminar and turbulent respectively. The square symbols show the measured mass transfer coefficient at each electrode height.

It is clearly shown that the measured mass transfer coefficients follow the laminar mass transfer correlations up to about 10^8 of Gr and follow turbulent mass transfer correlations from 10^9 of Gr.

5. Conclusions

This study sought the proper transition criteria for the natural convection flows; Ra and Gr. Using analogy experiment methodology, heat transfer problems were transformed to corresponding mass transfer problems.

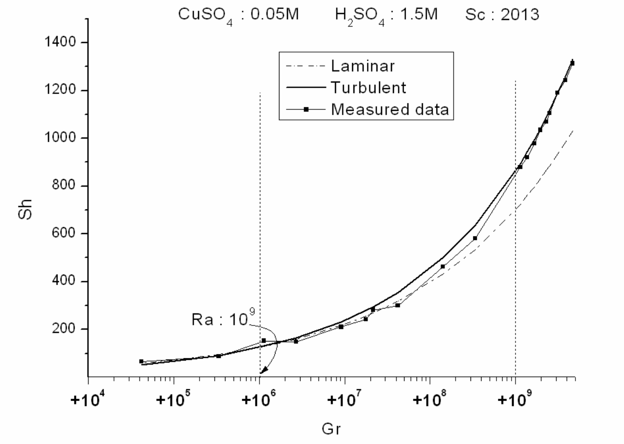

Fig. 2. The test results.

With the test facility of height 0.5 m, 10^{12} and 10^9 of Ra and Gr values were achieved. Also very high value of Sc number was achieved so that the difference between Ra and Gr could be clearly seen.

The test results showed that the Gr number of 10^9 is the proper transition criteria for the natural convection flow. The papers with similar conclusion can be found in the open literatures. The originality of this study is that the tests were performed at very high value of Sc, which corresponds to the Pr in heat transfer systems.

This study also shows the usefulness of the analogy experiment methodology using the electroplating system.

ACKNOWLEDGEMENTS

This study was sponsored by the Nuclear R&D Infrastructure Development Program of the MEST, Korea.

REFERENCES

[1] F. P. Incropera and D. P. DeWitt, Introduction to Heat Transfer 5th Ed., Wiley & Sons Inc. pp.364-411, 2001.
[2] A. Bejan and A. D. Kraus, Heat Transfer Handbook, Wiley & Sons Inc. Vol. 2, pp. 268-287, 1995.
[3] A. Bejan and J. L. Lage, The Prandtl Number Effect on the Transition in Natural Convection Along a Vertical Surface, Journal of Heat Transfer, Vol. 112, pp. 787-790, 1990.
[4] J. N. Agar, Diffusion and Convection at Electrodes, Discussion of Faraday Soc., pp. 27-37, 1947.
[5] T. B. Drew, et al., Advances in Chemical Engineering, Academic Press, New York and London, Vol. 10, pp.212-279, 1978.
[6] V. G. Levich, Physiochemical Hydrodynamics, Prentice-Hall, Inc., New York, 1962.
[7] J. R. Selman and C. W. Tobias, Mass Transfer Measurement by the Limiting Current Technique, Adv. Chem. Eng., 10, pp. 211-318, 1978.
[8] S. H. Ko, D. W. Moon and B. J. Chung, Applications of Electroplating Method for Heat Transfer Studies Using Analogy Concept, Nuclear Engineering and Technology, Vol. 38, No. 3, 2006.