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Natural Convection Mass Transfer Experiments in Horizontal Cylinders

Myeong-Seon Chae and Bum-Jin Chung*
Dept. of Nuclear and Energy Engineering, Institute for Nuclear Science and Engineering, Jeju Nat'l Univ. 66 Jejudaehakno, Jeju 690-756
**Corresponding author: bjchung@jejunu.ac.kr*

1. Introduction

Researches on the natural convection in horizontal cylinders have not been extensively studied. They are rare and most reported ones are for non-uniformly heated condition. It is difficult to find the literature on simple thermal condition. The natural convection in a horizontal cylinder is similar to that in an annulus with a cooled concentric inner cylinder and a heated outer cylinder.

The fluid heated by the inner surface of the cylinder flows upward along inner surface and then at the top, it flows downward along the vertical centerline of the cylinder. Two D-shaped natural convective flows are developed.

The heat transfer rate decreases as the thin boundary layer develops from the bottom toward the top and becomes thicker. At the top, the fluid is stably stratified and at the bottom it is unstably stratified. Thus the heat transfer rate is the maximum at the bottom and the minimum at the top [1].

Sarac and Korkut [2] carried out natural convection mass transfer experiments occurring at the external and internal surface of the cylinders by measuring the deposition of copper from aqueous copper sulfated solution containing sulfuric acid as a supporting electrolyte. The inside diameter of the cylinder was 0.6cm and concentrations of $CuSO_4$ were 0.025, 0.050, 0.10, 0.15, 0.20M. They suggested an empirical heat transfer correlation for a horizontal cylinder as follows;

$$Sh_d = 0.703(Gr_d Sc)^{1/4},\ \ 5.7\times10^9 < Gr_d Sc < 1.6\times10^{11} \qquad (1)$$

This study measured the natural convection mass transfers inside horizontal cylinders with varying the diameters of the cylinders at various angles. And it suggests a mass transfer correlation. A copper sulfate – cupric acid electroplating system was used as the mass transfer system.

2. Experiments

2.1 Test matrix and apparatus

Table 1 is the test matrix. The concentrations of H_2SO_4 and $CuSO_4$, which determine the material properties, were 1.5M and 0.05M, respectively. Prandtl number was 2,014. The lengths of cathodes were 9cm but the diameters were varied from 2cm to 25.9cm. Piecewise electrodes were used to measure the angle dependent mass transfer.

Table 1: Test matrix.

Pr	*L* (*cm*)	*D* (*cm*)	Ra_D	Gr_D	*No. of electrodes*
2014	9	25.9	1.5×10^{12}	6.6×10^{8}	10
		14.8	2.8×10^{11}	1.4×10^{8}	10
		9.9	8.2×10^{10}	4.0×10^{7}	6
		6.2	2.0×10^{10}	1.0×10^{7}	4
		3.2	2.8×10^{9}	1.4×10^{6}	2
		2.5	1.3×10^{9}	6.6×10^{5}	2
		2	6.8×10^{8}	3.4×10^{5}	-

Figure 1 shows the schematic of the test apparatus. An anode was located at the center of the cylinder (cathode). Two different test sections were used for each diameter: One with a single cathode and the other one with piecewise cathodes. Several current meters were used to measure the current of the each piecewise electrode.

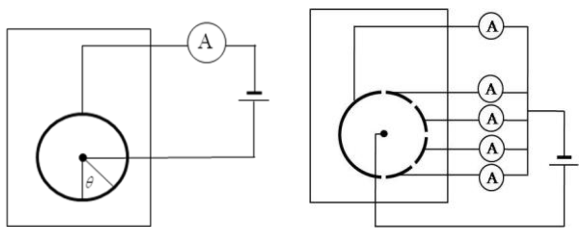

Fig. 1. A schematic of the test apparatus.

2.2 Mass transfer method using analogy concept

The cupric acid-copper sulfate (H_2SO_4-$CuSO_4$) electroplating system was adopted for the measurements of the mass transfer rates based on the analogy concept. The method was attempted by Levich [3] and an organized mass transfer correlation was developed by Selman and Tobias [4]. Chung et al. [5-6] have conducted a series of tests on applications of analogy-based experimental methodology.

3. Results and discussion

3.1 Comparison between results and correlation

Fig. 2 presents the test results with a single electrode and piecewise electrodes and the prediction from the correlation of Sarac and Korkut for various Ra_D's. The measured mass transfer rates for piecewise electrodes were in good agreements with the single electrode, and they are in consistent with the correlation, too.

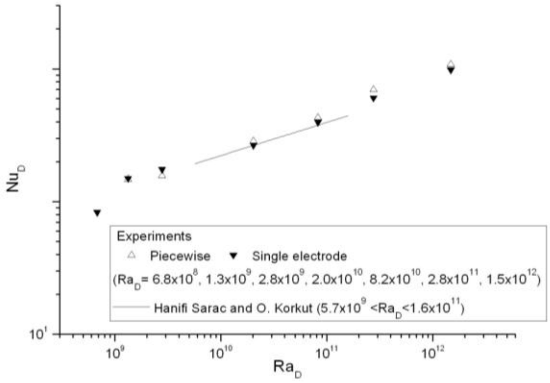

Fig. 2. Nusselt number experiment results comparison with correlation.

Except a very small Ra_D, the experimental results do not deviate significantly from the extrapolation of the correlation. At the very large value of Ra_D's (2.8×10^{11} and 1.5×10^{12}), the measured mass transfer rates were slightly higher than the values Nu_D's predicted from the correlation, which is limited to laminar. This seems to be caused by the flow transition to turbulent and this can be seen also in Fig. 4.

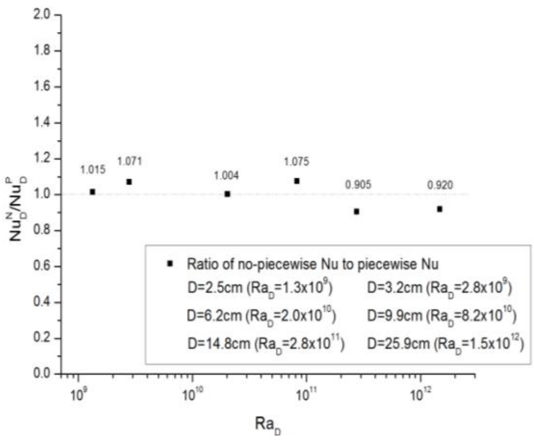

Fig. 3. Nusselt number compared no-piecewise to piecewise for semicircle.

3.2 Natural convections in horizontal cylinders

Fig. 3 shows the ratios of the measured mass transfer rates of the single electrode and the sum of the piecewise electrodes for each diameter of the cylinder. They are all around the unity and the influences of the gaps between piecewise electrodes are not much.

Fig. 4 presents the measured Nu_D values of piecewise electrodes starting from the bottom to the top for each diameter of the cylinder. The measured Nu_D values are based upon the current measured at the piecewise electrodes and thus they are the average Nu_D values for the angles between θ_i and θ_j. They simply decrease from at the bottom to the top for all diameters except 25.9cm, which are in consistent with the theory that the heat transfer rate decreases along the flow direction upward.

The decreasing slope of the average Nu_D values with the angle became steep as the diameter of the cylinder increases.

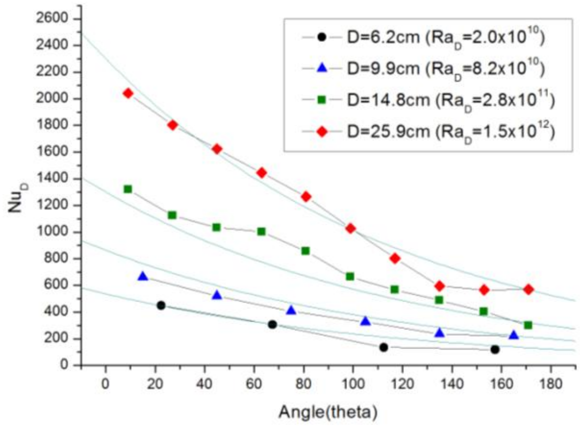

Fig. 4. Nusselt number as angle for diameter.

The Nu_D values for the top two piecewise elctrodes for diameter 25.9cm were constant, which seems to be caused by the turbulent transition. Based upon the test results a heat transfer correlation was except for the turbulent region as follows;

$$Nu_{Local} = 0.173 Ra_D^{0.33885} e^{-0.0082\theta} \quad (2)$$

4. Conclusion

Natural convection mass transfers inside horizontal cylinders were investigated for the cylinders of various diameters with piecewise electrodes for various angles. The analogy concept was adopted to expand the range of tests to turbulent region.

The measured mass transfer was highest at the bottom and decreased with the flow moving upward, in consistent with the literatures. With the cylinder of 25.9 cm diameter, the sign of turbulent transition was observed. Test results were formulated into a heat transfer correlation.

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