Natural Convection Heat Transfer of Two Vertically Staggered Cylinders

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1. Introduction

This study measured the natural convection heat transfer of two vertically staggered cylinders varying Ra_D, the vertical pitch-to-diameter, P_v/D and the horizontal pitch-to-diameter, P_h/D. The geometry frequently appears in heat exchangers and other engineering applications. This study has the relevance with the design of the test facility for PDRC (Passive Decay Heat Removal System) in SFR (Sodium-cooled Fast Reactor).

In the staggered arrangement, the heat transfer of the lower cylinder is unaffected by the presence of the upper cylinder. However, the heat transfer of the upper cylinder is affected by the plume developed from the lower cylinder on aligned of two vertically staggered cylinders [1]. When the spacing between two cylinders was less than the critical distance, the upper cylinder was affected more by the preheating effect. As the distance increases, the preheating effect decreases and the velocity effect increases [2].

2. Experiments

2.1 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 instead of the heat transfer experiments 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].

2.2 Test apparatus and matrix

The apparatus consisted of a water tank made of acryl with the top open. Two copper cylinders (cathodes) were mounted horizontally in a bank and a copper plate (anode) was located surrounding the two cylinders.

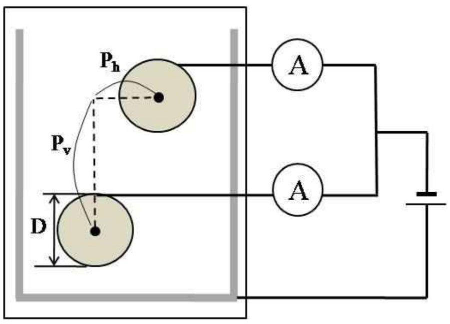

Fig. 1. The experimental equipment and system circuit

Table I presents the test matrix. The measurements were made by varying the P_v/D of 1.1~5 for laminar flow, the P_v/D of 1.02~2 for turbulent flow and the P_h/D of 0~2 in both laminar and turbulent flows. The Rayleigh number ranged from 1.5×10^8 to 2.5×10^{10} and Prandtl number was 2,014.

Table I : Test matrix.

Pr	*D* (*m*) (Ra_D)	P_v/D	P_h/D
2014	0.067 (2.5×10^{10})	1.02, 1.1, 1.5, 2	0, 0.2, 0.3, 0.5, 0.7, 1, 2
	0.012 (1.5×10^8)	1.1, 1.8 3, 5	0, 0.2, 0.5, 0.8, 1, 2

3. Results and discussion

3.1 Heat transfer of the lower cylinder

Fig. 2 presents the measured heat transfer rates for the lower cylinder and the correlations developed from a single cylinder in literature. The measured heat transfer rates at the lower cylinder were in agreement with the existing correlations. The heat transfer of the lower cylinder was unaffected by the presence of the upper cylinder [2].

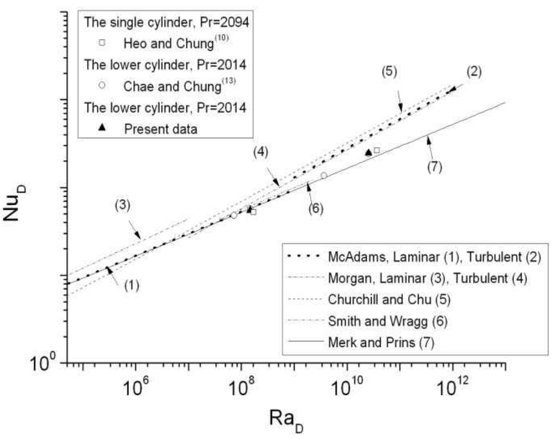

Fig. 2. Nusselt number of the lower cylinder compared with correlations for a single cylinder.

3.2 Heat transfer of the upper cylinder

Fig. 3 presents the measured Nu_D^U / Nu_D^L ratio with P_h/D and compared them with the Sparrow's experimental results. The measured results for the upper cylinder showed the dependence for P_v/D and P_h/D.

For small P_v/D when P_h/D was 0, the heat transfer of upper cylinder was smaller than that of the lower cylinder, because preheating effect of the plume

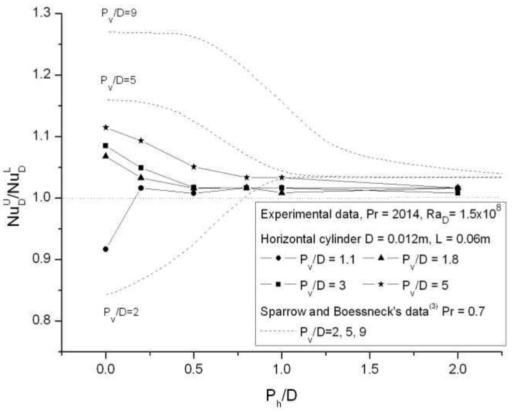

Fig. 3. Nu ratio as a function of horizontal Pitch-to-Diameter (Laminar).

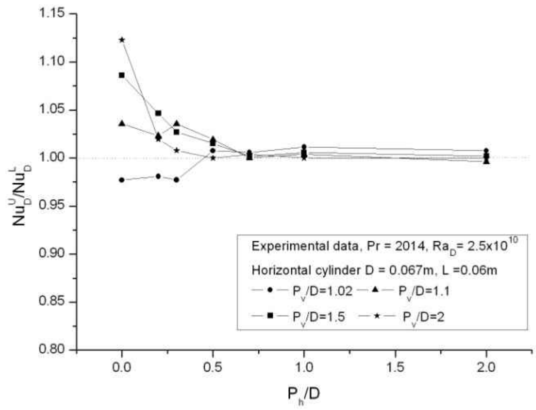

Fig. 4. Nu ratio as a function of horizontal Pitch-to-Diameter (Turbulent)

generated at the lower cylinder dominates. With increasing P_h/D at this P_v/D, the heat transfer rates of upper cylinder showed the enhancement and then became the same to the lower cylinder as the preheating effect vanished. Velocity effect dominates where P_v/D was 1.8~5, where the heat transfer of the upper cylinder is larger than that of the lower cylinder. At this P_v/D, with increasing P_h/D, the heat transfer of upper cylinder decreased and became the same to the lower cylinder due to the gradual decrease in the velocity effect. The plume arriving at the upper cylinder adds the initial velocity to the natural convection of the upper cylinder, and the upper cylinder is then situated in mixed convection condition.

The result of Sparrow and present work shows some discrepancies. It seems to be caused by the Chimney effect. Chimney effect is the increase of heat transfer rate when the plumes from the lower and upper cylinders are accelerated from overlapped thermal boundary layers [5]. With a very large Prandtl number fluid in this study, the thermal diffusivity is much smaller and the strong enhancement due to the chimney and side flow effects are not expected.

With increasing P_h/D the heat transfer rates of the upper cylinder showed the sharp enhancements at small P_v/D, and gradual increases at large P_v/D as the width of plume occurring at the lower cylinder became wider as the plume rises.

For turbulent flow, the heat transfer rate of upper cylinder larger than lower cylinder or similar as shown in Fig. 4. This is because the enhanced mixing of the turbulent flow causes an impairment of the preheating effect and an enhancement of the velocity effect and eddy[6]. The heat transfer rate of upper cylinder in turbulent flow was not much larger than laminar flow. This may be explained by the laminarization of the mixed convective flow[6]. In a turbulent situation, buoyancy-aided flow undergoes laminarization, as less slip between forced and natural convection is expected.

4. Conclusions

This study measured the natural convection heat transfer of two vertically staggered cylinders. The measured heat transfer rates for the lower cylinder agreed well with the existing correlations for a single cylinder. At the smallest P_v/D, the rising plume from the lower cylinder provides the upper cylinder with a preheated flow and the heat transfer rates of the upper cylinder decrease, but they increase very sensitively with the P_h/D. However at the largest P_v/D, the velocity effect dominates and the heat transfer rates of the upper cylinder were larger than that of the single cylinder, and they decrease less sensitively with the P_h/D. Even if the P_h/D is increased, the heat transfer rate of upper cylinder is higher than that of lower cylinder due to Chimney and Side flow effect. This work expanded the flow ranges to turbulent flows. With increasing P_h/D the heat transfer rates of the upper cylinder showed the gradual enhancements at small P_v/D, and sharply decreases at large P_v/D. This is because though the P_v/D is small, the enhanced mixing of the turbulent flow causes an impairment of the preheating effect and an enhancement of the velocity effect and eddy.

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