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Numerical Study on the Natural Convection of Two Staggered Cylinders Varying the Vertical and Horizontal Pitches and Prandtl Numbers

Jeong-Hwan Heo and Bum-Jin Chung
Department of Nuclear and Energy Engineering, Institute for Nuclear Science and Technology,
Jeju National University #102 Jejudaehakno, Jeju, 690-756, Korea
**Corresponding author: bjchung@jejunu.ac.kr*

1. Introduction

Natural convection heat transfer from two staggered cylinders has considerable relevance to a number of engineering applications including heat exchangers, heat storage devices, and cooling of electronic components [1]. The important factors affecting the heat transfer of staggered cylinders are the Rayleigh number based on the cylinder diameter (Ra_D), the vertical pitch-to-diameter ratio (P_v/D), the horizontal pitch-to-diameter ratio (P_h/D), and the number of cylinders [2] (Fig. 1). In the present research, natural convection heat transfer phenomena for two staggered cylinders are investigated numerically for laminar flow. Numerical simulations are performed for specified ranges of Pr, P_v/D, and P_h/D, with particular emphasis on very small P_v/D.

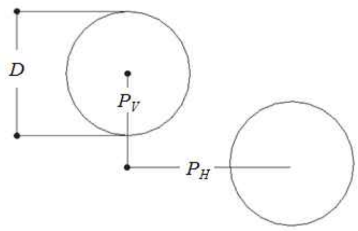


Fig. 1. Geometry of the staggered cylinders.

2. Previous study

In a staggered cylinder arrangement, the plume generated by the lower cylinder influenced the heat transfer of the upper cylinder via preheating and velocity effects. In the former, the hot plume that rose from the lower cylinder degraded the heat transfer of the upper cylinder. In the latter, the plume from the lower cylinder provided an initial velocity at the upper cylinder, increasing the intensity of the flow, and thereby improving the heat transfer of the upper cylinder. At smaller P_v/D and $P_h/D = 0$, the preheating effect was dominant. At larger P_v/D and $P_h/D = 0$, the velocity effect became dominant [3]. As increased P_h/D, the preheating and velocity effect is gradually disappeared and the heat transfer rate of the upper cylinder approached that of a single cylinder, due to the lessened impingement of the plume from the lower cylinder. Nevertheless, the heat transfer of the upper cylinder remained slightly higher than that of a single cylinder due to side flow effect. This flow washed over the upper cylinder when it was situated at the side of the plume from the lower cylinder. The resulting mixed convective flow gave rise to a small enhancement of the heat transfer over that of the single cylinder [4]. When two cylinders are horizontal arrangement, the heat transfer of the two cylinders was nearly the same. However, when P_h/D was reduced, the heat transfer of the two cylinders was enhanced due to the increased flow drawn between the cylinders by the chimney effect, resulting from the overlapping of the two rising plumes. The chimney effect became stronger with Ra_D. For very small P_h/D, the heat transfer of the two cylinders was dramatically reduced because their boundary layers overlapped [5]. The lower cylinder is not affected by the presence of the upper cylinder, and that the heat transfer rate of the lower cylinder is equal to that of a single horizontal cylinder [3-5].

3. Numerical studies

The FLUENT 6.2 was used [6]. The GAMBIT mesh was used to generate the 2D model. Simulations were carried out using the Boussinesq approximation and the temperature of heated wall was kept at 400 K for a constant temperature condition. The segregated solver was used with a first-order upwind algorithm for momentum and energy in the laminar model. For pressure discretization, the standard algorithm was adopted, whereas the SIMPLE algorithm was used for pressure–velocity coupling discretization. Table 1 presents the test matrix for FLUNET simulations.

Table I: Test matrix.

D (m)	Ra_D	Pr	P_v/D	P_h/D
0.012	1.5×10^8	0.7, 5, 20, 1,000, 2,014	1.1, 5	0, 0.2, 0.5, 0.8, 1.0, 2.0

4. Results and discussion

Figure 2 shows the Nu_D ratios of the upper (a) and lower (b) cylinder to a single cylinder for $P_v/D = 5$ and D = 0.012 m. The squares, circles, triangles, inverted triangles, and diamonds represent the Pr values of 2,014, 1,000, 20, 5, and 0.7, respectively.

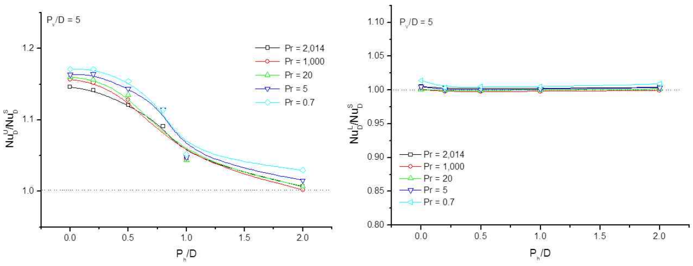
In Fig. 2 (a), when $P_h/D = 0$ the Nu^U_D/Nu^S_D were greater than unity for all Pr, due to the velocity effect. As P_h/D increased, the Nu^U_D/Nu^S_D decreased rapidly, since the upper cylinder moved out of the impingement zone of the plume from the lower cylinder. Further increases in P_h/D produced a gentle reduction of the Nu^U_D/Nu^S_D. The Nu^U_D/Nu^S_D for large P_h/D was still slightly larger than unity, due to the side flow effect.

In Fig. 2 (b), all the lines were virtually horizontal, indicating a constant value roughly equal to the maximum Nu^L_D/Nu^S_D of around 1.01. Thus, the heat transfer of the lower cylinder was unaffected by the presence of the upper cylinder.

Figure 3 shows the Nu_D ratios of the upper (a) and lower (b) cylinder to a single cylinder for P_v/D = 1.1 and D = 0.012 m. The squares, circles, triangles, inverted triangles, and diamonds represent the Pr values of 2,014, 1,000, 20, 5, and 0.7, respectively.

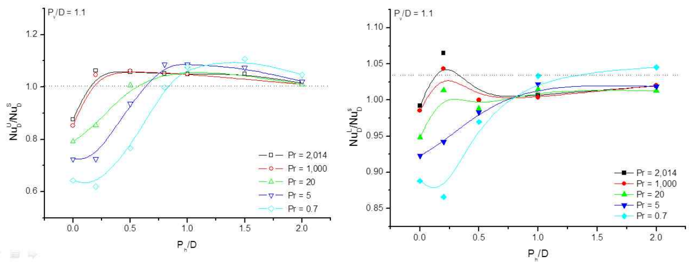
In Figure 3 (a), at P_h/D = 0, the Nu^U_D/Nu^S_D were smaller than unity for all Pr, due to the preheating effect. As Pr increased, the preheating effect was weakened, and the heat transfer rate recovered because the thermal boundary layer was thin. As P_h/D increased, the Nu^U_D/Nu^S_D also increased because the preheating effect was reduced, while the velocity effect was maintained. The Nu^U_D/Nu^S_D reached a peak at the P_h/D value corresponding to the minimum preheating effect and maximum velocity effect. The peak shifted to higher P_h/D values as Pr decreased, because the preheating effect covered a wider range with smaller Pr. With further increases in P_h/D, the Nu^U_D/Nu^S_D was reduced to a value slightly larger than 1, due to the side flow effect. A notable result is that for small Pr and a P_h/D of around 0.2, an inflection point appeared in the Nu^U_D/Nu^S_D curves due to the 'sweep effect'. In this effect, when the pitch was very small the plume from the lower cylinder did not break upon impingement at the upper cylinder, and swept one side of the upper cylinder more thoroughly, leading to stronger preheating (Fig. 3 (b)).

In Fig. 3 (b), when P_h/D = 0, the Nu^L_D/Nu^S_D was smaller than 1 due to the 'stagnant flow effect'. In this effect, the fluid between the lower and upper cylinder was trapped by the rising plume generated by the lower cylinder, and disturbed the convective heat transfer(Fig. 3 (a)). At smaller Pr, the stagnant flow effect was stronger due to the thinner thermal boundary layer. For large Pr, when Ph/D increased to 0.2, the Nu^L_D/Nu^S_D also increased due to the chimney effect, which enhanced the ascending flow as the plumes from the upper and lower cylinders merged to form a single plume. However, for small Pr, the Nu^L_D/Nu^S_D decreased due to the sweep effect caused by the thick boundary layer. With further increases in P_h/D, the preheating, sweep, and chimney effects almost disappeared, and the Nu^L_D/Nu^S_D approached unity.



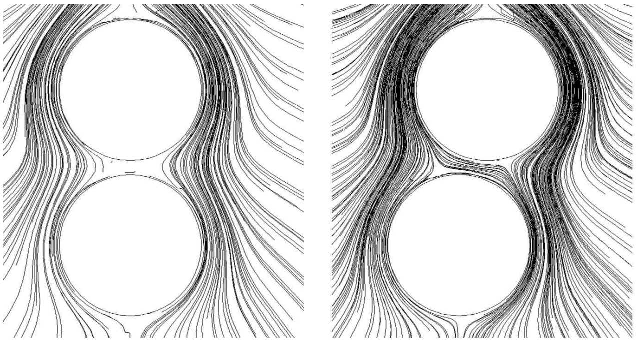
(a) The upper cylinder (b) The lower cylinder

Fig. 2. Nu_D ratios for P_v/D = 5 and varying P_h/D



(a) The upper cylinder (b) The lower cylinder

Fig. 3. Nu_D ratios for P_v/D = 1.1 and varying P_h/D



(a) P_h/D = 0 (b) P_h/D = 0.2

Fig. 3. Streamlines for Pv/D =1.1 and Pr = 0.7

5. Conclusions

Natural convection heat transfer phenomena for two staggered cylinders were investigated numerically. The influence of the plume from the lower cylinder on the upper cylinder could be described in terms of preheating, velocity, side flow effects, and sweep effect according to P_v/D, P_h/D, and Pr. For very small P_v/D, the heat transfer of the lower cylinder was affected by the presence of the upper cylinder, due to stagnant flow, sweep, chimney, and side flow effects according to P_h/D, and Pr.

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