Natural convection heat transfer of two heating spheres with pitch-to-diameter ratio

Seong-Il Baek, Je-Young Moon, Dong-Ho-Shin 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

1. Introduction

Natural convection heat transfer of spherical particle appears in various engineering applications such as the pebble bed reactor, spherical lamps, vaporization and condensation of fuel droplet, etc [1–3]. In particular, when the failure of electrical power in the nuclear power plant occurs, the decay heat of pebble bed reactor is removed by the natural convection. Although the natural convective flow in the packed bed is important, the existing studies are rare [4]. In the pebble bed reactor, the spherical type fuels are randomly stacked. It is difficult to analyze the complex flow pattern inside the packed pebble bed due to the random packing structure of bed [4,5]. Thus, the studies on the heat transfer phenomena between adjacent spheres in the packed bed is needed.

We performed the natural convection experiments to investigate the influence of pitch-to-diameter ratio on heat transfer of two heating spheres. Based on the analogy concept, mass transfer experiments were conducted using a copper sulfate-sulfuric acid ($CuSO_4$-H_2SO_4) electroplating system. The horizontal and vertical pitch-to-diameter ratios were varied 0-1.06 and 0-7, respectively. The diameter (*d*) of sphere was 6 mm, which corresponds to Ra_d of 1.83×10^7. Also, the *Sc* corresponding to *Pr* was 2014.

2. Theoretical background

2.1. Natural convection of a single heating sphere

Figure 1 shows the natural convective flow of a sphere. The buoyant flow starts at the bottom along the surface of the sphere and separates the plume from the upper part of the sphere. The local heat transfer rate reaches the maximum at the bottom of the sphere and the minimum at the top. The form of the plume varies with the diameter of the sphere and affects the heat transfer of the sphere.

For low Ra_d, a laminar boundary layer is formed and then the plume rises from the uppermost part [2]. As increased Ra_d, a transition to turbulence occurs and the plume rises at the upper part of the sphere which is relatively lower [1]. When the diameter of the sphere exceeds the critical Ra_d of 3×10^8, the transition occurs [6].

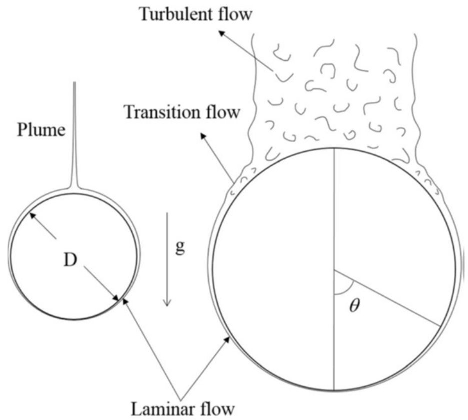

Fig. 1. Natural convection on a sphere [6].

2.2. Natural convection of two cylinders in different arrangement

The experimental studies on the natural convection heat transfer of two spheres are rare. However, many studies for two cylinders have been performed [7–15]. Figure 2 presents the schematic of two heating spheres in arrangement.

Sparrow and Niethammer [7] studied natural convection heat transfer on two inline cylinders for Rayleigh numbers from 2×10^4 to 2×10^5 and P_v/d from 2 to 9 with a uniform wall temperature boundary condition. They found the plume from the lower cylinder influences the heat transfer of the upper cylinder through the preheating effect and velocity effect. First, the preheating effect means that the heated plume of the lower cylinder preheats the solution near the upper part of the cylinder, which leads to the decline of the heat transfer of the upper cylinder. Second, the velocity effect represents that the plume of the lower cylinder increases in the heat transfer of the upper cylinder by providing initial velocity to the flow from the upper cylinder.

Yuncu and Batta [8] performed a numerical study of heat transfer on two inline cylinders. Their results were similar to those of Sparrow and Niethammer [7].

Sparrow and Boessneck [9] researched the natural convection heat transfer on two cylinders for P_v/d of 2 to 9, P_h/d of 0 to 3 and Ra_d of 2×10^4 to 2×10^5. As P_h/d increases, a side-flow effect occurs and the heat transfer of the upper cylinder is improved. It is because the plume from the lower cylinder sweeps the side of the upper cylinder

Heo et al. [10] carried out the experiments and numerical simulations on the natural convection heat transfer for two cylinders with P_h/d varying from 0 to 2 and P_v/d varying from 1.1 to 5 while Ra_d ranged from 1.5×10^8 to 2.5×10^{10} and Pr ranged from 0.7 to 2,014. Heo et al. [10] also reported the preheating effect, velocity effect and side-flow effect. Furthermore, they found the Pr effect. Fig. 3 represents the temperature and velocity fields of two cylinders for $P_v/d = 5$ and $Pr = 0.7$ to 2,014, where the blue, yellow, and red indicate the lowest, medium and highest values, respectively. As Pr increases, the thermal boundary layer becomes relatively thin and the momentum boundary layer becomes thick. Thus, for high Pr, the preheating effect is weakened and velocity effect is dominant.

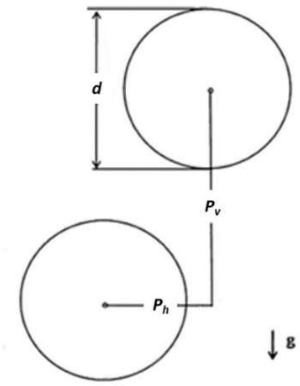

Fig. 2. Schematic of Two heating spheres in arrangement.

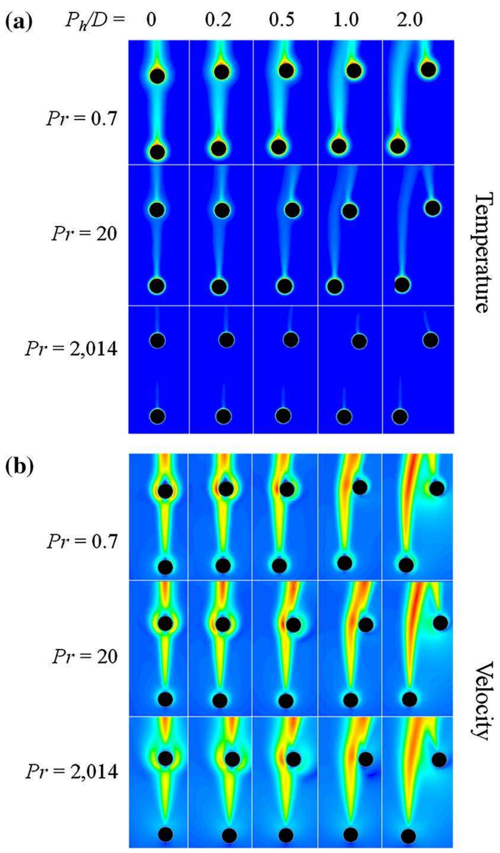

Fig. 3. Temperature and velocity fields of two cylinders for $P_v/d = 5$ [10].

3. Experimental set up

3.1. Experimental methodology

Heat and mass transfer systems are analogous, as the governing equations for two phenomena are same [16]. Hence, using the analogy concept, heat transfer experiments can be performed as mass transfer experiments. We adopted a copper sulfate-sulfuric acid ($CuSO_4$-H_2SO_4) electroplating system as the mass transfer experiments [17].

In order to calculate the mass transfer coefficient (h_m), we used the limiting current technique with an electroplating system. The physical properties were calculated using the correlation provided by Fenech and Tobias [18] and the mass transfer coefficient (h_m) is defined as:

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

Further details of the technique can be represented Bae and Chung [19] and the several applications of the technique for various geometries are in the studies of Chung et al. [20–23].

3.2. Test matrix and apparatus

Table 1 presents the test matrix. The Sc corresponding to Pr was 2,014. Also, The sphere diameter (d) was 6 mm, which corresponds to Ra_d of 1.83×10^7. The horizontal and vertical pitch-to-diameter ratios were varied 0 to 1.06 and 0 to 7, respectively.

Figure 4 shows the electric circuit which consisted of the cathode spheres, anode, power supply and data acquisition (DAQ) system. The thickness and length of the copper rod connected to the cathode sphere are 3 mm and 100 mm, respectively. The heating spheres were submerged in the top-opened acryl tank (W 300 mm × L 300 mm × H 350 mm) filled with the copper sulfate-sulfuric acid ($CuSO_4$-H_2SO_4) solution. The copper anode of cylindrical shape was positioned at the corner of the acryl tank away from the cathode to minimize the effect of the anode position. The potential was controlled using the power supply (Vüpower K1810) and the electric current was measured using the DAQ system (NI 9227).

Table I: Test matrix of two heating spheres in an open channel.

Sc	***d* (mm)**	***Ra_d***	**Position**	
			Ph/d	***Pv/d***
2,014	6	1.83×10^7	0	1.06, 1.5, 2, 3, 5, 7
			0.47	1.06, 1.5, 2, 3, 5, 7
			0.76	1.06, 1.5, 2
			1.06	1.06, 1.5, 2

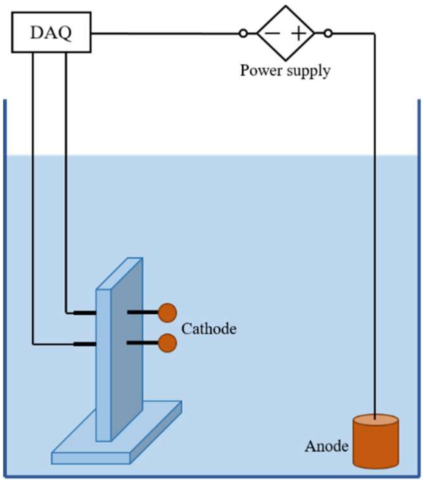

Fig. 4. Schematic design of the test electric circuit.

4. Results and Discussion

4.1. Natural convection of two inline spheres

Figure 5 indicates the Nu_d ratios of the upper sphere to the lower sphere for inline arrangement (P_h/d = 0). For all cases of P_v/d, the Nu_d measured at the lower sphere agreed well with the result of single sphere in open channel. The heat transfer of the upper cylinder was declined by the decrease of the P_v/d up to P_v/d = 2, due to the preheating effect. For P_v/d = 3–7, the heat transfer of the upper sphere similar to the lower sphere.

In the existing studies, the Nu_d ratio with the increase of P_v/d was higher than 1 due to the velocity effect, but this study did not. It was because the plume was differently formed depending on the geometry.

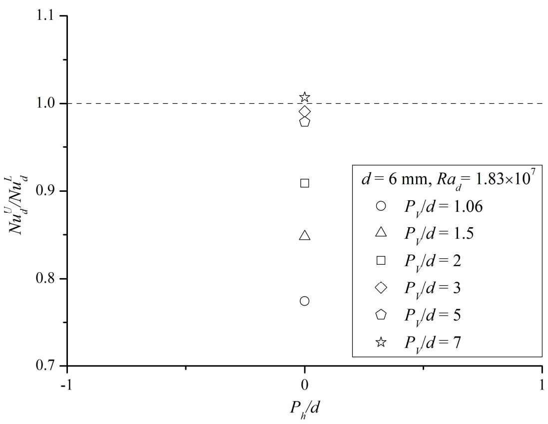

Fig. 5. Nu_d ratios of the upper sphere to the lower sphere for varying P_v/d and P_h/d = 0 (Inline arrangement).

4.2. Natural convection of two staggered spheres

Figure 6 shows the Nu_d ratios of the upper sphere to the lower sphere for staggered arrangement. For all cases of P_v/d, the Nu_d measured at the lower sphere agreed well with the result of single sphere in open channel.

When the P_h/d was 0.47, the heat transfer of upper sphere for P_v/d = 3–7 was not influenced by the lower sphere. However, in the cases of P_v/d = 1.06–2, the heat transfer of the upper sphere was higher than that of the lower sphere. It was because the side-flow effect occurred as the increase of the horizontal pitches. These results were consistent with those for two cylinders in the existing studies [9-10]. As P_h/d was greater than 0.76, the upper sphere was not affected by the lower sphere.

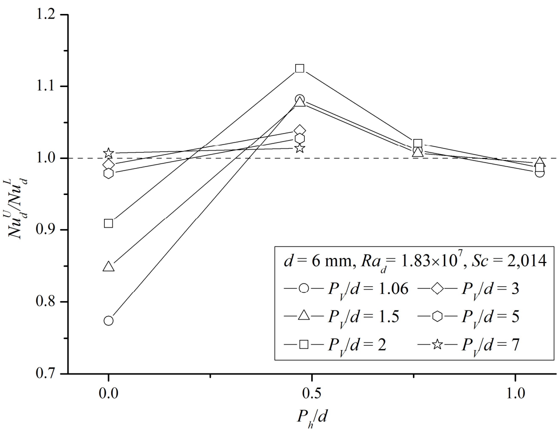

Fig. 6. Nu_d ratios of the upper sphere to the lower sphere for varying P_v/d and P_h/d.

5. Conclusions

The natural convection heat transfer experiment was investigated by varying horizontal and vertical pitches of two heating spheres. We used the $CuSO_4$-H_2SO_4 electroplating system of mass transfer based on the analogy concept between heat and mass transfer.

In case of the inline arrangement (P_h/d=0), the plume from the lower sphere caused the preheating effect, and the heat transfer of the upper sphere decreased. When the P_v/d increased, preheating effect became weak and the heat transfer similar to the lower sphere. The existing studies for two cylinders reported the velocity effect became dominant. This difference was caused by the formation of plume for each geometry.

In case of the staggered arrangement (P_h/d = 0.47), the side-flow effect occurred. However, as the P_h/d was greater than 0.76, the plume from the lower sphere did not affect the upper sphere.

Based on the results in this study, we will expend the experimental cases for sphere diameter and pitch.

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