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Investigation of natural convection heat transfer of a heated sphere at contacts points in a packed bed

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1. Introduction

Packed bed geometry can provide a large heat transfer area compared to the same volume of other geometries, which is useful in various engineering application like heat exchangers, thermal energy storage systems, and molten salt reactors. Randomly stacked particles in the packed bed cause complex flow paths and heat transfer that are difficult to analyze.

Spheres in the packed bed form multiple contact points with adjacent spheres. This can lead to the heat transfer impairment due to the reduced heat transfer. However, several researchers have reported that the natural convection heat transfer of a single heated sphere in a packed bed is similar to that observed in an open pool, indicating that the effects of contact points can be negligible [1-3]. A few studies have proposed that the redevelopment of the boundary layer around the contact point compensated for heat transfer loss due to the reduction in heat transfer area caused by the adjacent spheres [1-2]. These can provide valuable understanding into the local heat transfer mechanism in the packed bed. Nevertheless, there remains a shortage of experimental data on local flow and heat transfer within a packed bed to support these hypotheses.

In this study, the effect of the contact points from adjacent spheres on the heating sphere was analyzed. We performed the mass transfer experiments using a copper sulfate-sulfuric acid ($CuSO_4$-H_2SO_4) electroplating technique based upon the analogy between heat and mass transfer systems. To explore the effects of flow regime on the contact point, the diameter of sphere was varied from 15.8 mm to 40 mm, and the corresponding Ra_d was from 3.35×10^8 to 5.43×10^9. The location of the contact point was chaged from 0° to 180° based on the heating sphere. In addition, the local heat transfer of the heating sphere according to the location of the contact point was visualized by using plating patterns reflecting local heat transfer in the electroplating system. These support our findings and can provide insight into natural convection heat transfer in the packed bed.

2. Theoretical background

2.1 Natural convection heat transfer in packed bed

Achenbach conducted mass transfer experiments focusing on natural convection heat transfer for a single sphere in both packed beds and open pools. The Pr ranged from 0.7 to 2.5, and Ra_d was less than 10^7 [3]. The experimental results demonstrated that the heat transfer for a single sphere in a packed bed was equivalent to that in an open pool. Furthermore, the heat transfer in the packed bed was unaffected by the porosity.

2.2 Visualization of flow separation

Kitamura et al. investigated the lift-up point by visualizing the natural convective flow of a single sphere as shown in Fig. 1 [4]. Experiments were carried out in the range of $5\times10^6 < Ra_d < 4\times10^{10}$ for water and $4\times10^5 < Ra_d < 4\times10^9$ for air. Fig. 2 shows flow separation at a range of Ra_d. According to their results, lift-up point moves to downward as Ra_d increases. Lift-up point is where the natural convection flow developed from the lower part of the sphere was separated from the upper part and ascended. This point is corresponding to the transition point. They reported that this separation point of single heating sphere goes down as Ra_d increased.

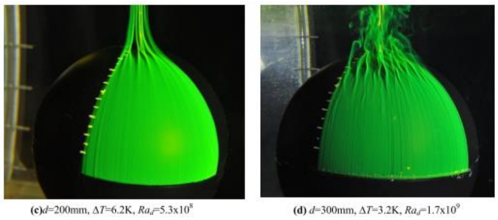

Fig. 1. Visualizations of natural convective flows induced around spheres [4].

3. Experimental setup

3.1 Methodology

We performed the mass experiment by adopting $CuSO_4$-H_2SO_4 electroplating system. Upon application of the electric potential, copper ions migrate towards the cathode and are reduced, resulting in a decrease in the concentration of copper ions around the cathode. The density difference caused by the difference in concentration at cathode generates buoyancy to analogy a natural convective heat transfer phenomenon. Therefore, transfer of copper ions from the anode to the cathode corresponds to natural convection heat transfer.

To calculate the mass transfer coefficient (h_m) while overcoming the limitation of measuring the concentration of bulk fluid near the surface (C_b), the limiting current technique was adopted. In the electroplating system, the current initially increases and reaches a limiting current condition where all copper ions near the cathode are exhausted. At this condition, the surface concentration is considered to be zero, which parallels the condition for constant temperature in heat transfer systems. Thus, the mass transfer coefficient (h_m) can be obtained only by determining the limiting current density and bulk concentration as follow. Further details of the technique is explained in a previous study [5].

$$h_m = \frac{(1-t_n)I_{lim}}{\mathrm{nF}C_b}. \qquad (1)$$

3.2 Test matrix and experimental apparatus

Table 1 indicates the test matrix for the experiments. The sphere diameter was 0.0158 m and 0.04 m, which corresponds to Ra_d of 3.35×10^8 and 5.43×10^9, respectively. Copper sulfate-sulfuric acid ($CuSO_4$-H_2SO_4) of 0.05 M and 1.5 M was used as working fluid corresponding to *Sc* of 2,014. The contact positions of the non-heating were varied from 0° to 180°..

Table 1. Test matrix

Sc	*d* (m)	Ra_d	Contact angle (°)
2,014	0.0158	3.35×10^8	0, 30, 60, 90, 120, 150, 170, 180
	0.04	5.43×10^9	

Figure 2 illustrates the experimental circuit. Cathode copper sphere are connected to the insulated copper rod. The anode was positioned in the corner of the tank bottom to minimize its impact. [6]. The acrylic tank is filled with a $CuSO_4$-H_2SO_4 solution. Power is supplied through a power source (Vüpower K1810), and current is measured and recorded using a DAQ (NI 9227).

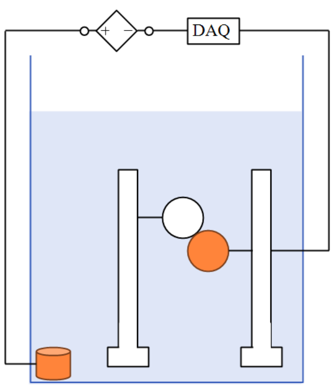

Fig. 2. Electric circuit and experimental apparatus.

4. Results and discussion

4.1 Comparison with existing correlation for single sphere

Fig. 3 verifies the agreement with the experimental results and the existing natural convection heat transfer correlation of a single sphere [4,7,8]. The line indicates the existing correlations, and the circle and triangular symbols show the heat transfer experimental cases for *d* = 15.8 mm and 40 mm, respectively. The experimental results coincide with existing correlations: the average relative error with the correlation was within 5% for *d* = 15.8 mm case and for *d* = 40 mm case.

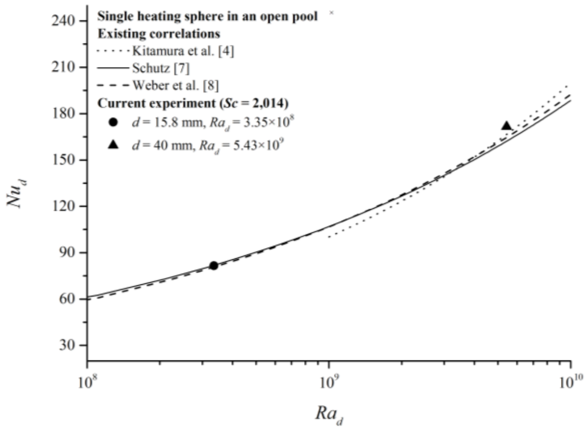

Fig. 3. Comparison test results with correlations.

4.2 Influence of contact point on natural convective heat transfer on sphere

Figure 4 shows Nu_d of the sphere according to the contact location. The solid and dashed lines indicate the heat transfer result of a single sphere, and the closed symbols indicate the heat transfer result with a contact point. . In the all cases of *d* = 15.8 mm, the Nu_d was similar to that of single sphere, regardless of the presence of contact point owing to compensatory effects. Compensation arises from the enhancement of heat transfer due to a thinned boundary layer and the weakening of heat transfer due to a reduced heat transfer area.

The cases for *d* = 40 mm also largely follow the same trends as the case for *d* = 15.8 mm. However, for case with 170–180 degree of contact point, the Nu_d was decreased compared to other cases. This is because at the top of the sphere, which is beyond the transition point, there is no area for the redevelopment of the boundary layer to compensate for heat transfer loss. Therefore, the contact point after the transition point weakens heat transfer, as it cannot offset the decrease in heat transfer area caused by the redevelopment of the boundary layer.

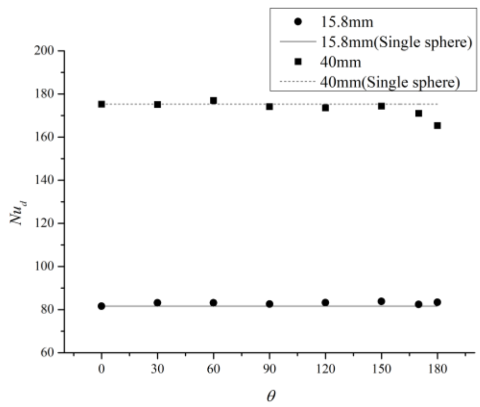

Fig. 4. Nu_d variations according to contact angle

4.3 *Visualization of heat transfer*

Figure 5 illustrates the plating patterns of d = 15.8 mm cases for the change in the position of the contact point. In all cases, areas where copper ions were not plated were observed at the contact points with the non-heating sphere. This means that heat transfer does not occur at the contact point, resulting in weakening of heat transfer. However, it was observed that copper ions were heavily plated in the vicinity of the contact area.

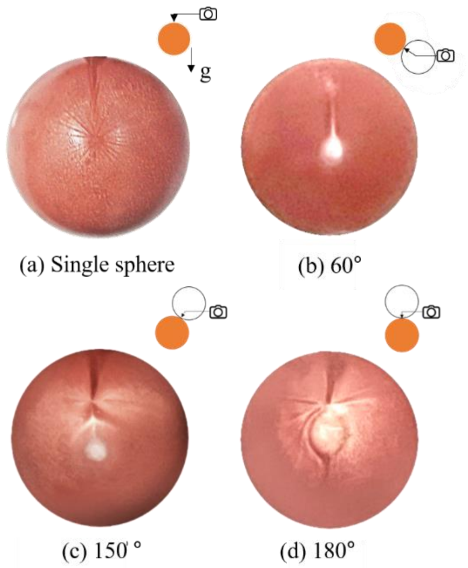

Fig. 5. Visualization of heat transfer at d = 15.8 mm.

Figure 6 depicts plating patterns of d = 40 mm cases for the change in the position of the contact point. In the 0–150° cases, the loss of heat transfer area due to contact and the reformation of the boundary layer were reflected (Fig. 6(a)–(c)). However, in cases above 150 degrees, it was observed that the contact point between the spheres intruded into the turbulent region (Fig. 6(d)). This contact point, located above the transition point(150°), impeded the regeneration of natural convective flow. As a result, there was no improvement in heat transfer from the reformation of the boundary layer. This occurred because the turbulent flow, which rises as the flow separates from the sphere, hindered the recovery of the boundary layer through the contact point. Thus, the contact point located at turbulent region did not compensate the loss of the heat transfer area.

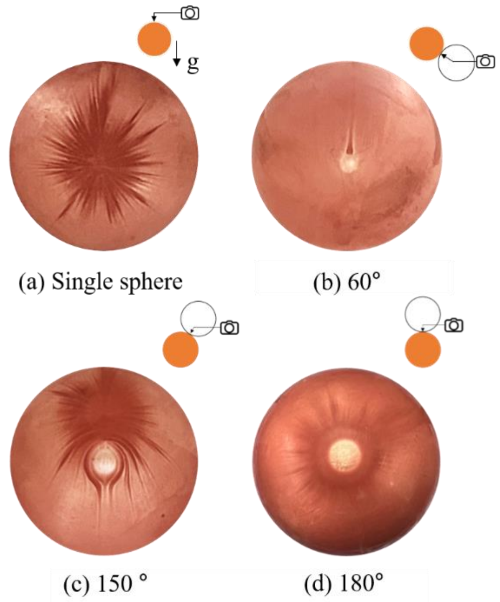

Fig. 6. Visualization of heat transfer at d = 40 mm.

5. Conclusions

Influence of the contact point on the natural convection heat transfer of a heated sphere was investigated. The heat transfer was measured and visualized wirh various diameters and contact point positions. The heat transfer results for a single sphere and a sphere with contact points were mostly identical as in previous studies. This is because the improvement in heat transfer due to the regrowth of the thin boundary layer compensates for the loss of heat transfer area caused by the contact point. However, at the contact point above the separation point, it was observed that the ascending turbulent flow disturbs the boundary layer redevelopment. The authors expect that these findings will provide fundamental insights for a better understanding of heat transfer in packed beds, which involve complex contact conditions.

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