Natural and forced convection heat transfer of single heating sphere in a packed bed

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1. Introduction

The packed bed has been adopted in many engineering applications such as the pebble fuel of nuclear reactors [1-3], thermal energy storage (TES) system [4], catalytic reactors [5], heat exchanger [6], etc.

As the performance of various applications is determined by the convective heat transfer in the packed bed, many studies have been performed over the past few decades [7,8]. Particularly, it is important to investigate the local heat transfer inside the packed bed, as the heat transfer distribution in the packed bed is non-uniform due to the sophisticated flow pattern by the packed bed structure [9,10]. However, relatively less studies were performed for the local heat transfer in the packed bed compared with the studies on the overall heat transfer of the bed [10,11]. It is because the rigorous analysis for the heat transfer mechanism in the packed bed is difficult due to the structure and flow characteristics of the packed bed [9].

van Antwerpen et al. [12] mentioned that a proper understanding of the packing structure in the bed is important to analyze the heat transfer mechanism inside the packed bed. Hence, a few studies on the local heat transfer in the packed bed were performed using a single heating sphere buried in the packed bed [1, 13-15]. Lee et al. [13,14] carried out the mass transfer experiments varying the axial and radial locations of single heating sphere in unheated packed bed for the natural and forced convective flows. They reported that the local porosity variation in the packed bed not affected the natural convection heat transfer. Also, the experimental results measured at the downstream zone was higher than those measured at the upstream zone due to the intensified eddy motion and vortex. Achenbach [15] showed the similar results for the forced convective flow. Abdulmohsin and Al-Dahhan [1] explored the local heat transfer coefficients in the packed bed for the forced convection by varying the radial locations along the height of the bed. They presented the heat transfer coefficients in the central region of the bed was smaller than those near the wall due to the porosity distribution in the packed bed.

This study investigated the influence of position on the heat transfer of single heating sphere buried in the packed bed varying the sphere diameter and sphere locations for the natural and forced convection. Mass transfer experiments were performed using copper sulfate-sulfuric acid ($CuSO_4$-H_2SO_4) electroplating system based on the analogy between heat and mass transfers. The Sc corresponding to the Pr was 2,014. The sphere diameter (d) was 0.006 and 0.010 m, which correspond

to Ra_d of 1.83×10^7 and 8.48×10^7. To change the sphere position, the r/R and z/H were 0–0.8 and 0.1–0.9, respectively. In the forced convection experiments, the superficial velocity (u_s) was varied from 0.01 to 0.58 m/s, which correspond to the Re_d of 63–5,076.

2. Experiments

2.1 Experimental Method

Heat and mass transfer systems are analogous as their governing equations are mathematically the same. Therefore, by the mass transfer experiments, the heat transfer problems can be solved effectively [16].

In this present work, a copper sulfate-cupric acid ($CuSO_4$-H_2SO_4) electroplating system was adopted as the mass transfer system. A cathode in this system was used to simulate the heated surface, as the buoyant force is induced by the reduction of cupric ions at the cathode surface and the resulting decrease in the fluid density. Given that the heat transfer coefficient (h_h) can be calculated from the heat flux and the temperature difference between the heated wall and the bulk, the mass transfer coefficient (h_m) was calculated from the mass flux (electric current) and the copper ion concentration difference at the cathode surface and bulk. This system provides a simple and relatively inexpensive means of investigating heat transfer systems [17].

In order to calculate the mass transfer coefficient, we used the limiting current technique [18]. When the applied electric potential increases, the current increases initially and then reaches a plateau. Despite further increase in the applied potential, the current does not increase as the reduction process of the cupric ions at the cathode is much faster than the transfer process of them from the anode to the cathode. The current at the plateau is called as the limiting current. At the limiting current condition, the Cs can be considered as 0 and h_m can be calculated with the limiting current density (I_{lim}) and the C_b only [19]. Thus, the h_m is defined as:

$$h_m = \frac{(1 - t_{cu^{2+}})I_{lim}}{nFC_b}$$

This technique has been developed by several researchers and are well-established as an experimental methodology [20-24].

2.2 Test matrix

Table I presents the test matrix of natural and forced convection experiments on the position effect of a single heating sphere in the packed bed. The Sc corresponding to Pr was 2,014. The duct diameter (D) was fixed to 0.06 m. The sphere diameter (d) was 0.006 and 0.010 m, which correspond to Ra_d of 1.83×10^7 and 8.48×10^7. The ratio of bed height to sphere diameter (H/d) was also fixed to 10.5 in order to maintain the effect of bed height (H) in each case of sphere diameter. The r/R and z/H were varied in 0–0.8 and 0.1–0.9, where r is the distance from the bed centerline and z is the distance from the top of packed bed. The average porosity in this study was 0.41. For forced convection experiments, the range of superficial velocity (u_s) was from 0.01 to 0.58 m/s corresponding to the Re_d of 63–5,076.

Table I: Test matrix.

| Sc | d (m) | Position | | Ra_d | Re_d |
		r/R	z/H		
2,014	0.006	0, 0.4, 0.8	0.1, 0.5, 0.9	1.83×10^7	63-3,050
	0.010			8.48×10^7	110-5,076

2.3 Experimental apparatus

Figures 1 and 2 show the schematic circuit of the test facility for the forced and natural convection experiments, respectively. In Fig. 1, the flow from a reservoir passed through a magnetic pump (PM-753PI, WILO), test section, and then returned back to the reservoir. Thus, the flow direction is downward. The flow rate was controlled by control and bypass valves and measured using an electromagnetic flowmeter (LF600, Toshiba). A single copper sphere acting as the heating sphere was buried in the glass beads. The copper sphere was electrically connected by the copper rod of 0.003 m. Also, a permeable grid was installed on the top and bottom of the test section.
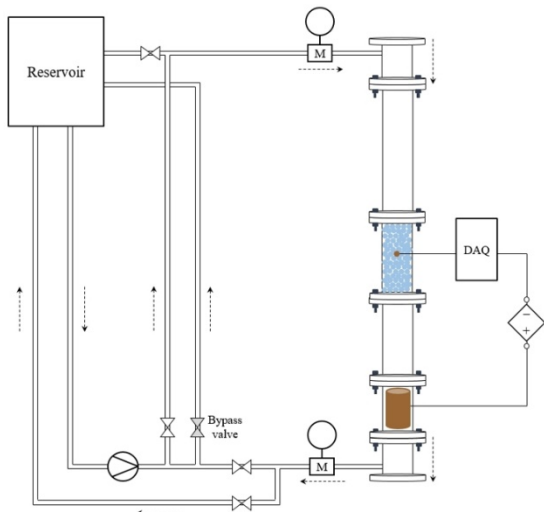
For the natural convection experiments, the same test section with the forced convection experiment was used. The test section was located in an open-topped acrylic container (0.30 m × 0.30 m × 0.42 m), as shown in Fig. 2. The support length of test section was 0.155 m.

The electrical potential was applied by a power supply (K1810, Vüpower) and the electric current was measured using the DAQ (NI-9227 & cDAQ-9179, National Instruments) system and LabVIEW.
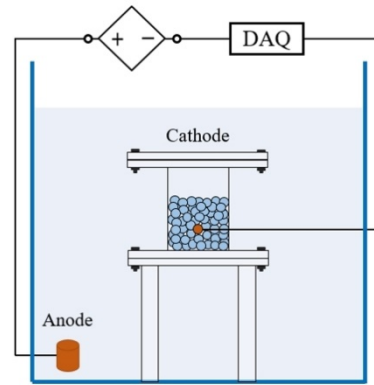

Fig. 2. Schematic of the test apparatus for natural convection experiment.

3. Results and discussion

3.1 Natural convection

Figure 3 shows the experimental results for natural convection heat transfer with regard to the axial and radial locations of a single heating sphere in the packed bed. For each sphere diameter, the Nu_d values measured at various positions were similar among themselves with the maximum error of 4%. It means the local heat transfer for the natural convection in the packed bed is not affected by the variation of axial and radial locations of single heating sphere.
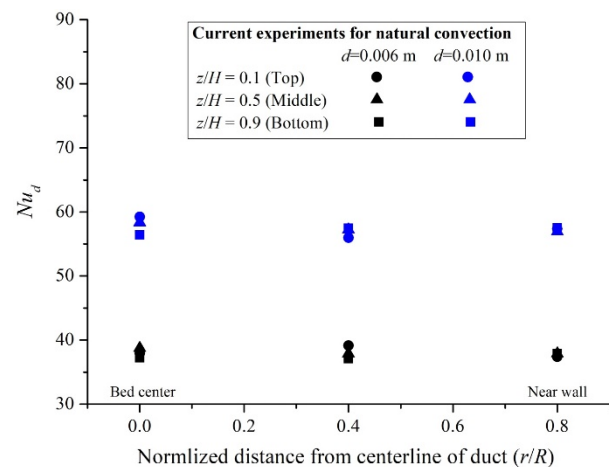

Fig. 1. Schematic of the test facility for forced convection experiment.

Fig. 3. The measured Nu_d according to the sphere positions inside the packed bed for the natural convection.

3.2 Forced convection

Figure 4 presents the measured Nu_ds' according to the Re_d and the different sphere positions for forced convection. For all sphere positions, the Nu_d increased gradually with the increase of Re_d.

In Figs. 4(a) and (b), the local heat transfer inside the packed bed was enhanced with the increase of z/H for various radial positions as the turbulence such as the eddy motion, vortex and recirculation was intensified by the porous structure of bed. Also, the results at the top (z/H=0.1) were same regardless of the variation in the r/R and smaller than averaged result for all positions. It is because the top section is the entrance zone of the packed bed.

Compared with Figs. 4(a) and (b), the variation of heat transfer according to the Re_d near wall region was sharper than the results in the center region of packed bed. This is due to the increase of the flow rate caused by the concentrated flow through the high porosity region. The same trend was observed for the other sphere diameter (d=0.006 m).
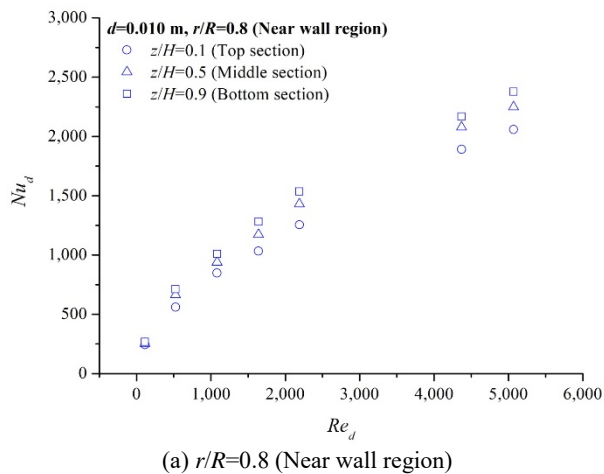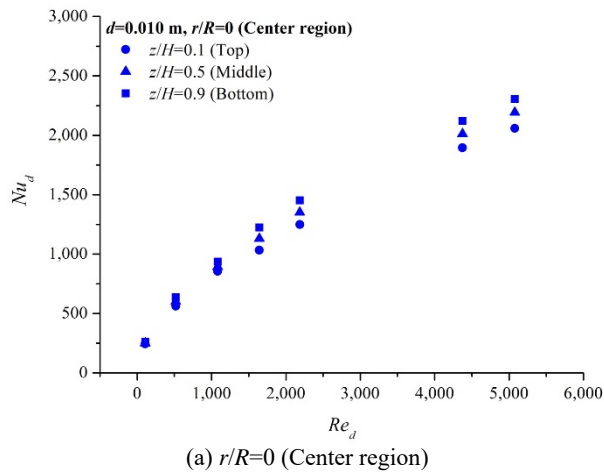

(a) r/R=0 (Center region)

(a) r/R=0.8 (Near wall region)

Fig. 4. Forced convection heat transfer according to the flow velocity and the different sphere positions for d=0.010 m.

4. Conclusions

The influence of the axial and radial positions on the heat transfer of single heating sphere in a packed bed for the natural and forced convective flow regimes was investigated with the sphere diameter of 0.006 and 0.010 m. We used the $CuSO_4$-H_2SO_4 electroplating system of mass transfer based on the analogy concept between heat and mass transfer.

For the natural convection flow, the local heat transfer in the packed bed was not influenced by the position variation of the single heating sphere. It is because the velocity of the natural convective flow is very slow due to the small buoyant force formed by the heating sphere.

For the forced convection flow, the heat transfer at various positions was gradually enhanced by the increase of flow velocity, which varied from laminar to turbulent flow. Due to the intensified the eddy motion, vortex and recirculation by the packing structure, the local heat transfer measured at the downstream zone of the packed bed was higher than that measured at the upstream zone. Moreover, the local heat transfer increased near the wall region compared with the bed center. It was because the higher porosity near wall caused the increase of the flow rate.

To develop the local heat transfer correlation for the forced convection in the packed bed, we will perform the forced convection experiments varying the flow velocity and sphere position with the extension of sphere diameter as the further study.

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