Anode influence on natural convection heat transfer of the packed bed in the electroplating system

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1. Introduction

Convective heat transfer in an packed bed has been applied in various engineering applications, such as pebble core of nuclear reactors, effective cooling of electronic devices, heat exchangers, chemical particle beds, solar air heaters [1-4]. In particular, the capability removing the heat produced at the core is a technical issue for safety and reliability of the pebble bed reactor (PBR) [2]. As the pebble fuels are piled up randomly, the flow path is complex. It caused the complicated flow phenomena around the pebble, such as the vortex, the turbulence flow, the stagnation flow, etc. [5].

Relatively less experimental studies were performed for natural convection of packed beds at all spheres heating condition as it is difficult to establish the uniformly heated condition for all spheres [4]. Lee et al. [4,6] verified that the ideal heated condition for spheres in the packed bed could be achieved using the electroplating system of mass transfer. However, as the total surface area of cathode spheres in the packed bed increases, the stability of measured current could be affected by the position and size of the anode.

This study investigated the influence of position and size of the anode on the natural convection heat transfer of the packed bed. Two types of packed beds were used: first, the single heating sphere in unheated packed bed and second, the all heating spheres in the packed bed.

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 sphere diameter was 0.006 m, which corresponds to Ra_d of 1.83×10^7. The duct diameter and bed height were fixed to 0.09 m and 0.04 m, respectively. The Sc, which corresponds to Pr, was 2,014.

2. Theoretical background

When the parts of the packed beds acted as the heat source, either the single heating sphere or all heating spheres in packed bed, the boundary layer and temperature difference between heat source and fluid were considered significantly. In the natural convection in the packed bed, the heat transfer is affected by the Rayleigh number (Ra_d), the Prandtl number (Pr) and not by the porosity (ε). As the Ra_d increases, the Nu_d increases due to the buoyancy. Also, the Nu_d enhances with the increases of Pr as the thermal boundary layer thickness decreases [1,7,8].

Achenbach [1] conducted both heat transfer and mass transfer experiments for the natural convection on a single heating sphere in packed beds and proposed a fitting correlation for $0.7 < Pr < 2.5$, $0.26 < \varepsilon < 1$ and $Ra_d < 10^7$. The proposed correlation means that the Nu_d increased with Ra_d and Pr regardless of the ε. Also, he reported that if the nearly perfect fluid mixing exists at the downstream on the sphere, the single heating sphere in unheated packed bed can simulate all heating spheres in packed bed.

Karabelas et al. [7] performed the mass transfer experiments for the natural convection heat transfer on a single heating sphere in packed beds using the electrochemical method. The test ranges were $\varepsilon=0.42$, $1.60\times10^3 < Sc < 6.06\times10^4$, $1.24\times10^7 < Ra_d < 3.24\times10^7$, which included laminar and turbulent flow conditions. Table I shows the aforementioned correlations of the natural convection heat transfer for a single heating sphere in packed beds.

Table I: Existing natural convection correlations for a single heating sphere in packed bed

Authors	Correlations and ranges
Achenbach (1995) [1]	$Nu_d = 2 + 0.56\left(\frac{Pr}{0.846+Pr}Ra_d^{0.25}\right)$ $0.7 < Pr < 2.5$, $Ra_d < 10^7$
Karabelas et al. (1971) [7]	$Nu_d = 0.46Ra_d^{0.25}$ $1.6\times10^3 < Sc < 6.06\times10^4$, $1.24\times10^7 < Ra_d < 10^9$

The measurement of temperature and velocity in the packed bed are difficult due to the complex packed structure. Also, the uniformly heated condition for all spheres in the packed bed is very hard to realize in the experiment. Most existing studies adopted either the single heating sphere in unheated packed bed or the insulated packed bed without heat source [1,7-11]. However, Lee et al. [4] reported that the natural convection heat transfer of all heating spheres in the packed bed was distinguished from that of single heating sphere in the packed bed due to the preheating and friction effect.

3. Experimental set up

3.1. Experimental methodology

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 [11].

A copper sulfate electroplating system offers high Rayleigh numbers with relatively small test facilities and exact measurements by electrical means. It is also free from experimental difficulties such as heat leakage to the external environment and radiation heat transfer [11]. In the electroplating system, the reduction of the cupric ion concentration near the cathode induces a local reduction of the fluid density compared to the surrounding fluid. Thus the cathode acts as a heated wall. The electric connection of the spheres can establish all the spheres heating condition easily.

In order to calculate the mass transfer coefficient (h_m), we used the limiting current technique with a copper sulfate–cupric acid ($CuSO_4$–H_2SO_4) electroplating system [12]. The mass transfer coefficient (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 [13-17].

3.2. Experimental apparatus and test matrix

Figure 1 shows the electric circuit. The sphere diameter (d) was 0.006 m, which corresponds to Ra_d of 1.83×10^7. The copper spheres are randomly piled into the acryl duct whose inner diameter (D) is 0.09 m. The bed height (H) were fixed to 0.04 m. The porosity (ε) of copper bed was 0.37. In order to ensure the natural convection, the cathode bed was rested on a permeable support grid. The cathode bed and the anodes were located in the top-opened tank (W 0.25 m × L 0.25 m × H 0.5 m) filled with the copper sulfate–cupric acid ($CuSO_4$–H_2SO_4) of 0.05 M and 1.5 M, respectively. The Sc, which corresponds to Pr, was 2,014. The electrical power was applied by a power supply (Vüpower K1810) and electric current was measured by the multi-meter (Fluke 15B).

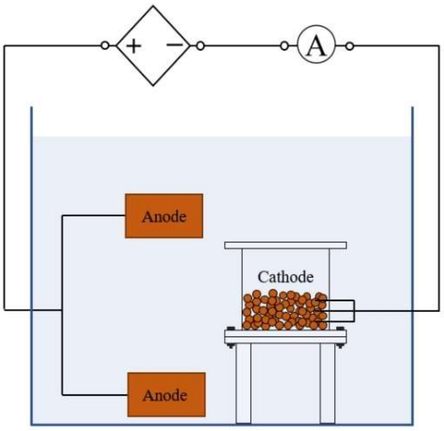
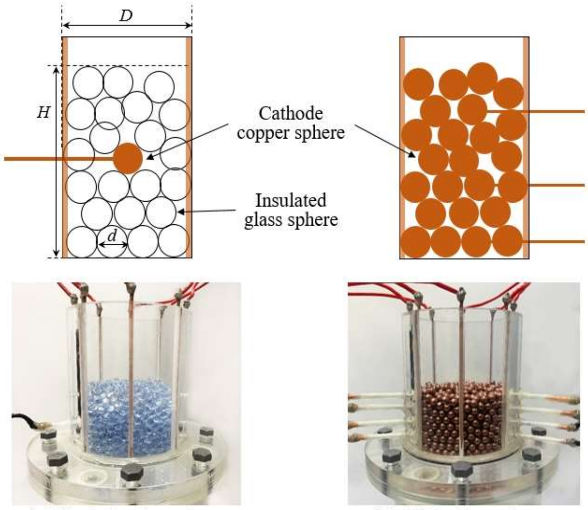


Fig. 1. The experimental apparatus and the electric circuit.

Figure 2 is the photographs of the test sections together with the schematic drawing to show the structure of packed bed. In Fig. 2(a), a single copper sphere simulating the heating sphere is located among the packed bed of glass spheres which simulate unheated packed bed. The single sphere was located at the packed bed axially and radially. Fig. 2(b) is the case for all heating spheres in the packed bed. In order to make secure electric contacts among copper spheres, six copper spheres were connected in parallel so that the contact electric resistance became zero. For both cases, the thickness of the support copper rod was 0.002 m.

To investigated the influence of position and size of the anode on the natural convection of the packed bed, the test matrices were determined as shown in Tables II and III. For cases 1 and 4, the copper anode rods with 0.003 m diameter and 0.13 m length were embedded in the furrows of 0.01 m on the wall of acrylic duct to avoid the direct electrical contact between the spheres and rods. For the others, the copper anode bundle was located at the bottom or top region in the tank shown in Fig. 1.



(a) Single heating sphere
in unheated packed bed

(b) All heating spheres
in the packed bed

Fig. 2. Schematics and photographs of the imbedded anode.

Table II: Test matrix for single heating sphere in a packed bed

Anode type	**Area ratio (A_c/A_a)**	**Position**	**Case No.**
Embedded rod	0.0130	Acryl duct wall	1
External bundle in the acryl tank		Bottom region	2
	0.0007		3

Table III: Test matrix for all heating spheres in a packed bed

Anode type	**Area ratio (A_c/A_a)**	**Position**	**Case No.**
Embedded rod	21.8	Acryl duct wall	4
External bundle in the acryl tank		Bottom region	5
	1.14		6
		Top region	7
		Bottom + Top region	8
Embedded rod + External bundle	1.08	Bottom region	9

4. Results and Discussion

4.1. Comparison of natural convection heat transfer between heating conditions

Figure 3 shows the measured Nu_d's with the heating conditions and anode types. The closed symbols of red color denote the Nu_d's measured for a single heating sphere in unheated packed bed and open symbols, the Nu_d's for all heating spheres in the packed bed. The Nu_d of single heating sphere in packed bed agreed well with the correlation proposed by Karabelas et al. [7]. However, the measured Nu_d's for all heating spheres in the packed bed show lower Nu_d than those for the single heating sphere about 15%. This is due to the preheating of the upstream flow, as reported by Lee et al. [4].

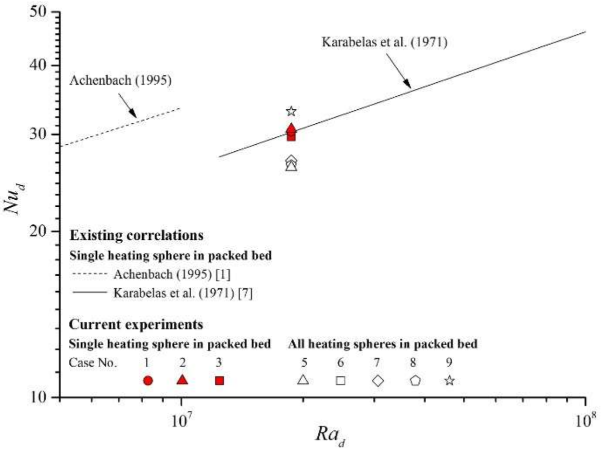


Fig. 3. The measured Nu_d with regard to heating conditions and anode types.

4.2. Influence of position and size of the anode

In Fig. 3, the shape of symbols denotes the position and size of the anode as indicated in Tables II and III. As the natural convection of a single heating sphere in packed beds was not affected by the position and size of the anode, the nearly constant Nu_d's were observed in Fig. 3. The maximum relative difference was 3.1 %. The area of single sphere was much smaller than anode area. Also, as the single sphere was located in the center of unheated packed bed, the distance from the anode was long enough not to be exposed to the direct cupric ion flux.

In contrast, the natural convections for all heating spheres in the packed bed are obviously affected by the position and size of the anode. The cases 6-8 were very similar as these cases had the same area ratio between cathode spheres and anode bundle and the different position in the tank. In these cases, the Nu_d's were very similar due to the areas of the anode and the cathode area similar and the sufficient distance was maintained between the cathode bed and the anode. Moreover, the Nu_d for case 5 was agreed well with that of case 6 within 1.6%. It means that if the anode is located at the outside of test section, the effect of the anode size can be minimized. However, the Nu_d of case 4 was not measured due to the unstable current data. This is caused by the deficiency of anode area and the proximity between cathode bed and anode rods. For case 9, The measured Nu_d showed higher Nu_d than those for cases 6-8 about 20%. The anode area was satisfied by using both embedded rods and external bundle as anode. However, as the cathode bed was adjacent to the anode rods, the cupric ion concentration at the edge of packed bed was higher. Thus, it means that cathode spheres located at the edge of bed were exposed to the different heating condition.

5. Conclusions

The influence of the position and size of the anode on natural convection heat transfer of packed bed was investigated using the two types of packed beds: first, the single heating sphere in unheated packed bed and second, the all heating spheres in the packed bed. Mass transfer experiments were carried out based on the analogy between heat and mass transfers, replacing heat transfer experiments. As the mass transfer system, the copper electroplating system was employed.

The results were compared with the existing heat transfer correlations for the single heating sphere in the packed bed, which they showed good agreement. Compared with this case, the natural convection heat transfers for all heating spheres in the packed bed decreased about 15% due to the preheating effect.

The influence of the position and size of the anode was only confirmed to the natural convection of all heating spheres in the packed bed. For these case, as the total surface area of cathode spheres in the packed bed increases greatly, the anode area should be satisfied as much as the cathode area.

Also, in order to control the homogeneous distribution of the cupric ion concentration in the packed bed, the anode should be located at a distance from the cathode.

Based on the results of this study, the design of the experimental apparatus including the position and size of the anode will be upgraded. Also, further studies such as the influence of particle diameter, porosity and bed height must be performed to develop the heat transfer correlation for the natural convection in the packed bed.

NOMENCLATURE

A	Area [m^2]
C	Molar concentration [kmole/m^3]
D	Duct diameter [m]
d	Sphere diameter [m]
F	Faraday constant [$94{,}485 \times 10^3$ C/kmole]
H	Bed height [m]
h_h	Heat transfer coefficient [W/m^2·K]
h_m	Mass transfer coefficient [m/s]
I	Electric current [A]
I_{lim}	Limiting current density [A/m^2]
Nu_d	Nusselt number ($h_h d/k$)
n	Number of electrons in charge transfer reaction
Pr	Prandtl number (ν/α)
Ra_d	Rayleigh number ($g\beta\Delta T d^3/\alpha\nu$)
Sc	Schmidt number (ν/D_m)
$t_{cu^{2+}}$	Transference number of Cu^{2+}

Greek symbols

ε	Porosity

Subscripts

a	Anode
b	Bulk
c	Cathode
d	Sphere diameter [m]

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