Influence of Bed Diameter (*D*) on the Natural Convection of a Packed Bed

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1. Introduction

The packed bed structure increases the heat transfer area and enhances the flow mixing by the complex porous structure. Owing to these characteristics, the packed bed has been applied to the various engineering applications including the fourth-generation reactor designs such as the High Temperature Gas-cooled Reactor (HTGR) and Pebble Bed Reactor (PBR) [1].

Numerous studies on the heat transfer for packed bed geometry have been conducted [2–10], but only a few of them have devoted to the natural convection [8,10]. Natural convection studies using all heating pebbles are rare due to the experimental difficulty in realization.

However, still the needs for the investigation of the natural convective heat transfer on a packed bed exist considering a Station Black Out (SBO) condition of a pebble bed reactor, where the decay heat may have to be removed by natural convection to prevent the core degradation.

In this study, we conducted natural convection experiments with all self-heating packed bed for various bed diameters (*D*). Mass transfer experiments were adopted using the copper sulfate-sulfuric acid ($CuSO_4$-H_2SO_4) electroplating system based on the analogy between heat and mass transfers. The sphere diameter (*d*) was 0.006 m, which correspond to Ra_d of 1.83×10^7. For all bed diameters (*D*), *H*/*d* was varied by 5, 10 and 20. The *Sc*, corresponding the *Pr*, was 2,014.

2. Literature survey

Noah et al. investigated heat transfer on a packed bed by using CFD modeling. They confirmed that the heat transfer on a packed bed is affected by many parameters, such as the Rayleigh number (Ra_d), Prandtl number (*Pr*), porosity (ε), bed height (*H*), etc [11].

Lee et al. (2017) carried out mass transfer experiments using an electroplating system for natural convection of a single heating sphere in an unheated packed bed and all heating spheres in a packed bed. They confirmed that the Nu_d of all heating spheres in the packed bed was lower than the Nu_d of a single heating sphere. It was because of the preheating according to bed height (*H*) [8]. Also, they proposed the correlation of all heating spheres in packed bed adding the multiplier for the bed height and sphere diameter.

$$Nu_d = (1.2 + 0.36 Ra_d^{0.25}) \times (d/H)^{0.7}$$
$$(Pr = 2{,}014,\ Ra_d = 1.8\times10^7)$$

Antwerpen et al. studied about the radial porosity variation in packed bed. They confirmed that the porosity near the wall sharply fluctuated due to the disturbance by the wall (Fig. 1). They proposed that the region of non-uniform porosity was defined about 4*d* from the wall [12].

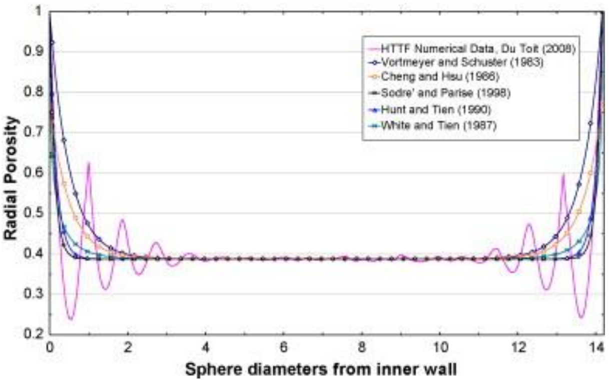


Fig. 1. Numerical result and correlations of radial exponential porosity [12]

Moon et al. investigated the influence of local porosity effect on packed bed in natural and forced convection. Mass transfer experiments were conducted, and the position of a heating sphere is varied to change the porosity. For the forced convection, the heat transfer of sphere near the wall is higher than the sphere center of the bed. It is because that the flow derives toward the large porosity. However, for the natural convection, the influence of the local porosity is not observed [2].

Since it is difficult to realize the experimental condition, only a few studies have been conducted on natural convective heat transfer for all heating spheres in a packed bed [2, 8]. Also, the influence of bed diameter (*D*) was not investigated. Thus, investigation is needed to know the influence of *D* on natural convection heat transfer of packed bed.

3. Experimental setup

3.1 Experimental methodology

We used a mass transfer experimental method based on the analogy concept between heat and mass transfer systems. The governing equations of two systems are mathematically the same. Thus, the heat transfer experiments can be replaced by mass transfer experiments [7,13].

We adopted the copper sulfate-cupric acid ($CuSO_4$-H_2SO_4) electroplating system as a mass transfer system to achieve high buoyancy with relatively small test rigs and uniform heating condition [14–17].

In the electroplating system, the reduction of the cupric ion concentration near the cathode surface induces a buoyancy. Thus, the cathode acts as a heated wall. The electric connection of the spheres can establish all the spheres heating condition easily.

To calculate the mass transfer coefficient (h_m), the limiting current technique was adopted. The h_m is defined as follow:

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

This technique has been developed by several researchers and are well-established as an experimental methodology [8, 16–18].

3.2 Test matrix

Table I shows the test matrix. In this study, the copper spheres were randomly packed in the cylindrical acryl pipe, whose diameter (d) was 0.006 m. Also, corresponded Ra_d was 1.83×10^7. The bed diameter (D) was 0.03, 0.06 and 0.09 m which corresponds to D/d = 5, 10, 15. The H was varied as 0.03, 0.06 and 0.12 m. All experiments were performed in 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.

Table I: Test matrix for all heating spheres in a packed bed varying the *D*/*d*

***d* (m)**	***D*/*d***	***H*/*d***	***Ra*_d_**	***Sc***
0.06	5	5, 10, 20	1.83×10^7	2,014
	10			
	15	5, 10		

3.3 Experimental apparatus

Figure 2 shows the electric circuit of the test apparatus. The porosity (ε) of the bed was 0.38 to 0.42. The spheres were packed on a permeable plastic grid net to enable the natural convection of fluid. The test apparatus was located in the top-opened acryl tank (W 0.3 m × L 0.3 m × H 0.35 m) filled with the copper sulfate–cupric acid solution. Also, the copper anode of sufficient size was located at the bottom of the tank. The fluid area above and below the test section was spaced at least 0.01 m. The electrical power was applied by a power supply (Vüpower K1810) and electric current was measured by the DAQ (NI 9227).

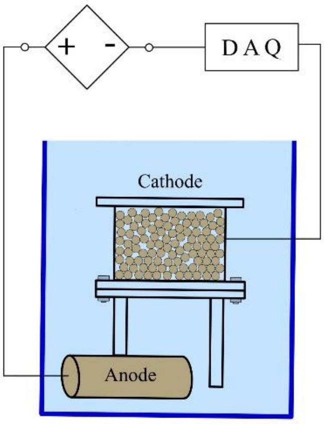
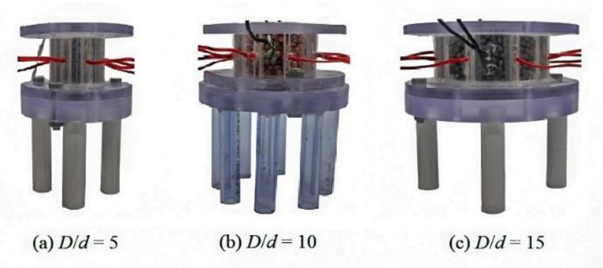


Fig. 2. The experimental apparatus and the electric circuit.

Figure 3 presents the photographs of the test sections. The bed diameters of Fig. 2 (a), (b) and (c) were 0.03, 0.06 and 0.09 m and bed heights were 0.06 m, all the same. The test sections were varied by bed diameter. We used cathode support copper rods, which have 0.003 m thickness, to apply voltage to the cathode in the test section. Also, we inserted 0.004 m thickness cooper rods into the side of the test section to support anode to make anode and cathode face each other.



(a) $D/d = 5$ (b) $D/d = 10$ (c) $D/d = 15$

Fig. 3. Photographs of the test apparatus varying the bed diameter (*D*).

4. Result and discussion

4.1. Comparison of measured Nu with existing study

Figure 4 compares the experimental results at $H/d = 5$ of this study with the existing correlation [19]. The correlation was developed for the natural convection of a single heating sphere in an open channel. The experimental results for $H/d = 5$ agree well with the correlation within the average error of 1.28%. This is because the H/d is small and all the spheres were contacted with the fresh fluid. Therefore, the average heat transfer of packed bed was similar to that of single sphere. Also, the effect of D/d was not observed.

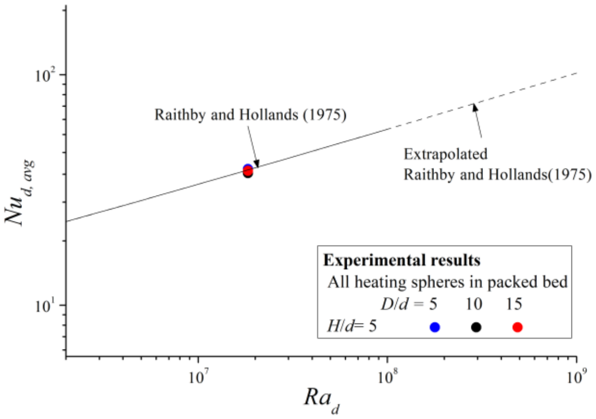


Fig. 4. The measured Nu_d with regard to D/d compared to correlation of Raithby and Hollands (1975) [19]

4.2. All heating spheres in the packed bed varying D/d and H/d

Figure 5 shows the experimental results according to the D/d and H/d. For all D/d, heat transfer on packed bed decreases as H/d increases. This is because of the preheating effect: due to the heated fluid from upstream, the heat transfer on spheres in downstream is impaired. It decreases the average heat transfer of packed bed.

However, the preheating effect is insignificant for D/d = 5. Because, for the small D/d, test section had a relatively large amount of fluid due to high porosity (average $\varepsilon = 0.42$) [12].

Meanwhile, D/d = 10 and 20 (average ε = 0.39, 0.37 in each case) cases had a wider low porosity region. Therefore, as the decline of volume to fluid ratio in the test section during D/d increases, the preheating effect was intensified and heat transfer was impaired as H/d increases.

Unlike forced convection, natural convection heat transfer in a packed bed did not show a wall effect [10]. Rather, in the natural convection in packed bed, the rising plumes for each sphere are merged and the flow was developed to the center of the bed. As a result, the preheating effect was intensified in the center of the bed, which is another cause of heat transfer degradation as D/d increases.

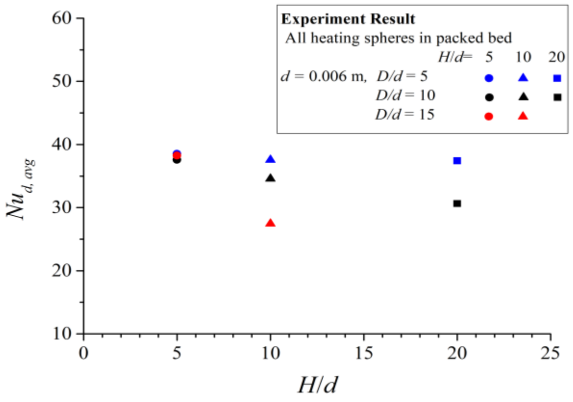


Fig. 5. Experimental results according to the D/d and H/d

5. Conclusions

The influence of the bed diameter (D) and height (H) on natural convective heat transfer of the packed bed was investigated by using the mass transfer experimental method.

The Nu_d for shortest bed (H/d = 5) was compared with existing natural convective heat transfer correlation for the single heating sphere in an open channel. The relative error between the experimental results and correlation is about 1.28 %. It is because that the packed beds were short and all spheres were exposed to the fresh fluid.

For all the D/d, the heat transfer on packed bed was impaired as H/d increases, due to the reinforcement of the preheating effect. The porosity is larger as the D/d smaller. Also, the plumes generated by each sphere are merged and flow toward the center of the bed. These two effects intensify the preheating effect, and the average heat transfer in packed beds is consequentially impaired.

Based on the results of this study, we will investigate the dominance of the D/d factor by expanding the test matrix for heat transfer on uniform self-heating packed beds.

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