

Natural convection heat transfer of the packed bed varying the bed height and sphere diameter

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1. Introduction

High Temperature Gas-Cooled Reactor (HTGR), which has the advantages of high efficiency, structural safety and high temperature formation, is considered as part of the promising nuclear system in Generation IV [1, 2]. Therefore, the heat transfer of packed bed structure has been investigated [3-10].

It is hard to realize the uniform self-heating condition for the experiments of all heating spheres in packed bed. Thus, a few experiments for all heating spheres in the packed bed have been performed [9].

When the reactor operates in normal condition, the coolant is pumped to remove the heat of pebble bed core. However, when the forced convection is lost by the accident, the heat of core should be removed by natural convection [11]. Thus, the study on natural convective heat transfer for self-heating spheres in the packed bed is essential.

We carried out the natural convection experiments for all heating spheres in the packed bed varying the bed height (H) and sphere diameter (d). Mass transfer experiments were adopted using the copper sulfate-sulfuric acid ($\text{CuSO}_4\text{-H}_2\text{SO}_4$) electroplating system based on the analogy between heat and mass transfers. The diameters of sphere were 0.004, 0.006 and 0.010 m, which correspond to Ra_d of 5.43×10^6 – 8.48×10^7 . For $d=0.006$ m, H/d was varied from 4.2 to 50. For the other diameters, H/d was fixed at 10. The Sc , corresponding the Pr , was 2,014.

2. Theoretical background

There are only a few experiments of natural convection heat transfer for all heating spheres in packed bed [10, 12-13]. It is because that the uniformly heating condition for all spheres in the packed bed is 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. [3-8]

Achenbach [3] carried out heat and mass transfer experiments for the natural convection on a single heating sphere in packed beds. The fitting correlation was suggested for $0.7 < Pr < 2.5$, $0.26 < \varepsilon < 1$ and $Ra_d < 10^7$. The proposed correlation expresses that regardless of the ε the Nu_d increased with Ra_d and Pr .

Karabelas et al. [4] performed the electrochemical experiments of mass transfer for the natural convection heat transfer on a single heating sphere in packed beds. He proposed a correlation, and the test ranges were ε

$$=0.42, 1.60 \times 10^3 < Sc < 6.06 \times 10^4, 1.24 \times 10^7 < Ra_d < 3.24 \times 10^7$$

Lee et al. [9] performed mass transfer experiments using the electroplating system for natural convection of a single heating sphere in unheated packed bed and all heating spheres in packed bed. They reported the Nu_d of all heating spheres in packed bed is lower than Nu_d of a single heating sphere because of the preheating. They developed the heat transfer correlation of all heating spheres in the packed bed by adding the multiplier for the bed height. However, this empirical correlation included the experimental errors on the anode influence.

Table I shows the aforementioned correlations of the natural convection heat transfer in a single heating sphere and all heating spheres in packed beds.

Table I: Existing natural convection correlations of packed bed

Authors	Correlations and ranges
Achenbach (1995) [3]	$Nu_d = 2 + 0.56 \left(\frac{Pr}{0.846 + Pr} Ra_d^{0.25} \right)$ $0.7 < Pr < 2.5, Ra_d < 10^7$
Karabelas et al. (1971) [4]	$Nu_d = 0.46 Ra_d^{0.25}$ $1.6 \times 10^3 < Sc < 6.06 \times 10^4,$ $1.24 \times 10^7 < Ra_d < 10^9$
Lee et al. (2017) [9]	$Nu_d = (1.2 + 0.36 Ra_d^{0.25}) \times (d/H)^{0.7}$ $Pr=2,014, Ra_d=1.8 \times 10^7$

3. Experimental set up

3.1 Experimental methodology

Heat and mass transfer systems are analogous as their governing equations and parameters are mathematically the same. [8, 14]. We adopted a copper sulfate-cupric acid ($\text{CuSO}_4\text{-H}_2\text{SO}_4$) electroplating system as the mass transfer. This experimental method based on the analogy concept is well-established [9, 16-19].

Using the mass transfer coefficient (h_m) is defined as:

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

The transfer of cupric ions from anode to cathode corresponds to heat transfer, which is easily and

accurately measured by the electric current. Most of all, the by using this methodology, isothermal heating condition can be easily established experimentally by applying the electric potential between the electrodes [9].

3.2 Experimental apparatus and test matrix

To investigate the influence of H and d on natural convection heat transfer of the packed bed, the test matrix was determined as shown in Table II. The copper spheres were randomly stacked into the acryl duct whose inner diameter (D) was 0.06 m. The sphere diameter (d) was 0.004, 0.006 and 0.010 m, which corresponds to Ra_d of 5.43×10^6 - 8.48×10^7 . The H was varied as 0.025–0.30 in $d=0.006$ m. Also, in $d=0.004$ and 0.010 m, H was fixed at 0.04 and 0.10 m, respectively. Every experiments are performed in copper sulfate–cupric acid ($\text{CuSO}_4\text{-H}_2\text{SO}_4$) of 0.05 M and 1.5 M, respectively. The Sc , which corresponds to Pr , was 2,014.

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

D (m)	d (m)	H (m)	Ra_d	Sc
0.06	0.004	0.04	5.43×10^6	2,014
	0.006	0.025, 0.06, 0.12, 0.18, 0.24, 0.30	1.83×10^7	
		0.010	0.10	

Figure 1 shows the electric circuit of test apparatus. The porosity (ϵ) of copper bed was 0.40-0.46. The cathode bed was placed on a permeable support grid to ensure the natural convection. The test apparatus was located in the top-opened tank (W 0.25 m \times L 0.25 m \times H 0.68 m) filled with the copper sulfate–cupric acid solution. Also, the copper anode was positioned at the bottom of the tank. The electrical power was applied by a power supply (Vüpower K1810) and electric current was measured by the DAQ (NI 9227).

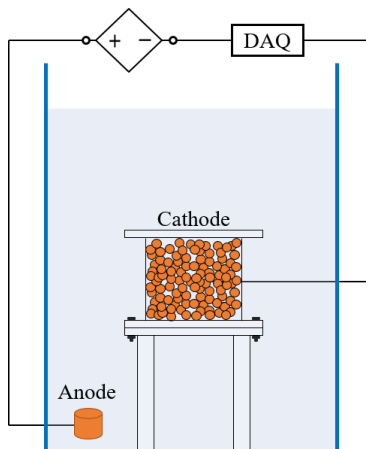


Fig. 1. The experimental apparatus and the electric circuit.

Figure 2 presents the photographs of the test sections.

The bed height of Fig. 2(a), (b) and (c) were 0.06, 0.12 and 0.24 m, respectively. The test section was changed according to H . In order to make electric contact among copper spheres and reduce the electric resistance, more and more spheres were connected in parallel as the H increases. The thickness of the support copper rod was 0.002 m ($d=0.004$ m) and 0.003 m ($d=0.006, 0.010$ m).

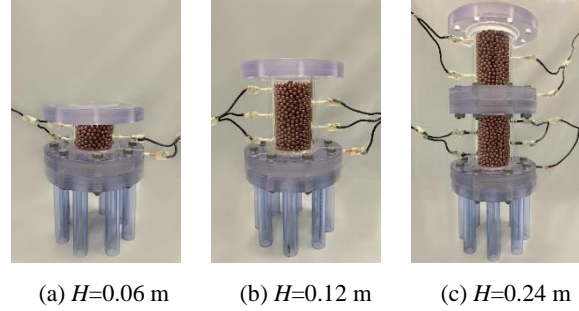


Fig. 2. Photographs of the test apparatus varying the bed height (H).

4. Results and Discussion

Figure 3 compares the experimental results of this study with the correlations of Achenbach (1995) and Karabelas et al. (1971). When the H/d is 4.2, the experimental results agree well with Achenbach's correlation within 4.4%. However, the Karabelas et al.'s correlation is lower than experimental results about 22.4%.

The difference between the experimental results and correlations increases with the increase of H due to the preheating effect. In the experiments of all heating spheres in packed bed, the downstream layer of packed bed encounters the heated bulk fluid which reduces the heat transfer.

In Fig. 4, as the H increases, the variation of Nu_d decreases because the temperature of the bulk fluid converges to the surface temperature of the sphere. Therefore, the Nu_d constants after $H/d=40$.

In Fig. 3, spherical symbols represent the results of all heating spheres in packed bed with regard to the d by fixing $H/d=10$. The measured Nu_d increases with Ra_d . However, when the d increases, the hm decreases (Fig. 5). It is because the boundary layer thickness becomes thicker as d increases.

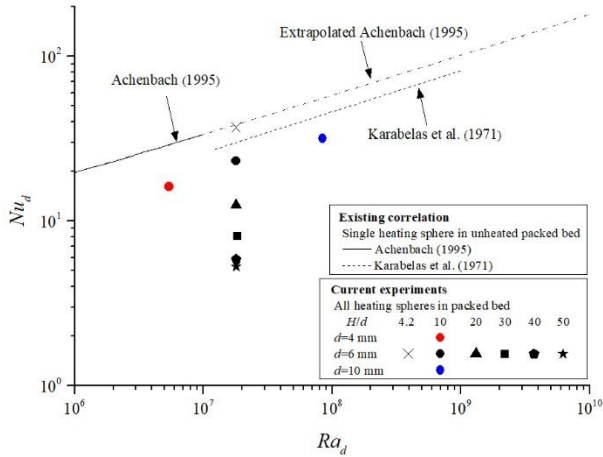


Fig. 3. The measured Nu_d with regard to bed height (H) and sphere diameter (d).

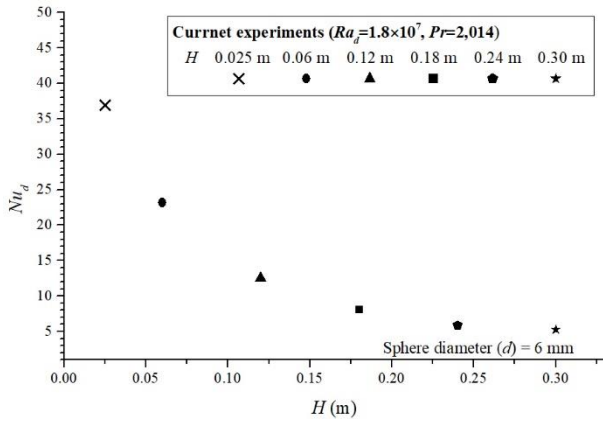


Fig. 4. Experimental results varying the bed height (H) in packed bed.

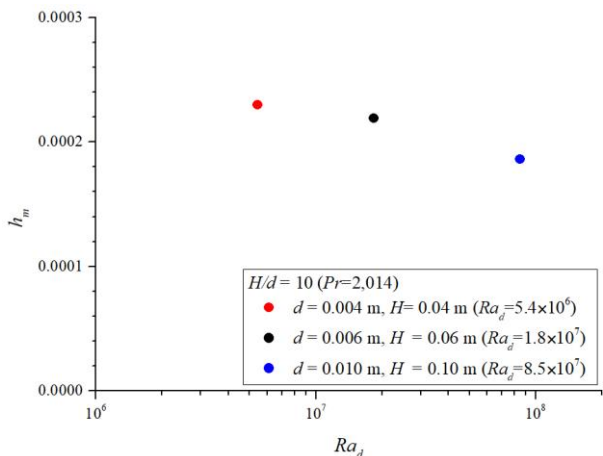


Fig. 5. The measured h_m with regard to bed height (H).

5. Conclusions

The influence of the bed height and the sphere diameter on natural convection heat transfer of packed bed was investigated. Mass transfer experiments were conducted based on the analogy between heat and mass transfer, replacing the heat transfer experiments.

The experimental results according to the bed height

were compared with the existing heat transfer correlations for the single heating sphere in the packed bed. The relative error between the results and the Achenbach's correlation (1995) is at least 4.4% for $H=0.025$ m, and the difference increases as the bed height increases due to the preheating effect. However, the variation of the Nu_d decreases as the bed height increases. It is because that the bulk fluid temperature converges to the sphere surface temperature.

The effect of sphere diameter on $H/d=10$ is confirmed in all heating spheres in packed bed. As the sphere diameter increases, h_m is decrease, because the boundary layer thickness becomes thicker.

Based on the results of this study, we will expand the test matrix to clarify the effects of the bed height and the sphere diameter on all heating spheres in packed bed condition. Also, we will develop the correlation that can predict the Nu_d according to H/d on natural convection heat transfer in pebble bed.

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