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Forced Convection Heat Transfer of Heat Generating Spherical Packed Beds

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1. Introduction

The pebble bed reactor has been considered as a candidate high temperature reactor type, which is one of the Generation-IV reactor concepts [1]. In the case of PBMR-400(Pebble Bed Modular Reactor-400), the core of reactor is filled with about 45,000 spherical fuels. As the fuels are piled up randomly, the flow path is complex and complicate phenomena around a fuel sphere occur by stagnation flow, vortex, flow separation, and so on [2].

Relatively less experimental studies were carried out for all heated sphere in packed beds at forced convective condition. Because it is hard to simulate to make the uniformly heated condition for all spheres. And it is difficult to measure the temperature and velocity of fluid due to the complicate structure of packed beds. Some experimental studies were performed for a single heated sphere buried in unheated packed beds [3–5]. The existing studies assumed that if the fluid mixing exists at the downstream on the sphere nearly perfect, the heated sphere can simulate the conditions of all heated sphere in packed beds [3]. While, most of the studies for packed beds heat transfer in forced convection were carried out numerically for all heated spheres. [2, 6–7]. However, numerical study is limitary since numerical method is difficult to simulate random packed beds.

This paper was experimentally studied in two parts: first, the forced convective heat transfer from single heated sphere varying Re_d and second, the all heated sphere in packed beds varying the height of packed beds and Re_d.

2. Background

2.1 Forced convection heat transfer in packed beds

The basic idea for treatment of heat transfer for packed beds is to consider the situation for individual particle [3]. If there are appropriate quantities of length scale, velocity and geometrical function, it is sufficient to correlate the results of the single heated particle with all heated sphere in packed beds [8].

The dominant influence variables are Re_d, ε (Porosity). The forced convection heat transfer in packed beds is proportional to Re_d where the d is a particle diameter. The statistical parameter porosity ε for a packed beds is defined as follows:

$$\varepsilon = 1 - \frac{V_s}{V_t} \qquad (1)$$

The V_s is a volume of spheres and V_t is a total volume of packed beds.

The forced convection heat transfer experiments were performed for a heated sphere embedded in unheated packed beds. Abdulmohsin and Al-Dahhan [5] performed experimental studies for packed beds at $5 < Re_d < 6\times10^3$. The heat transfer measured for varying position of single heated sphere vertically along the centerline in packed beds, and radially at the middle elevation. Wakao and Kaguei [4] carried out the experimental studies for packed bed at $20 < Re_d < 7.6\times10^3$, $0.7 < Pr < 1$ and suggest correlation. Achenbach [3] performed the forced convection heat transfer experiments and the mass transfer experiment, in range of $Re_d/\varepsilon \le 7.7\times10^5$ and $1 < Re_d/\varepsilon < 2.5\times10^4$ respectively and proposed empirical correlation.

Park et al. [2] carried out the temperature and velocity field in BCC (Body Centered Cubic), FCC (Face Centered Cubic) using numerical method. Ferng and Lin [6] performed numerical studies on forced convection heat transfer for fixed packed beds as BCC, FCC varying the layers of each lattice. The calculated Nu_d is close to existing correlation, stacking the unit lattices. Hassan [7] carried out the temperature and velocity fields in fixed packed beds of BCC structure for numerical method using LES (Large Eddy Simulation).

2.2 Existing correlations

Several investigators performed forced convective heat transfer experiments for a heated single sphere in packed beds and proposed correlations. Gnielinski [8, 9] suggested the semi-empirical correlation in range of $Re_d/\varepsilon \le 2\times10^4$, $0.26 < \varepsilon < 0.935$, $0.6 < Pr < 10^3$. Wakao and Kaguei [4] proposed correlation at $20 < Re_d < 7.6\times10^3$, $0.7 < Pr < 1$. German Nuclear Safety Standard Commission (KTA) [10] recommended a correlation at $100 < Re_d < 10^5$, $0.36 < \varepsilon < 0.42$ using system code. Achenbach [3] carried out the heat transfer experiments for $Re_d/\varepsilon \le 7.7\times10^5$ and the mass transfer experiments for $1< Re_d/\varepsilon < 2.5\times10^4$ respectively and developed empirical correlation. Table I shows the summary of the correlations. In Table I, Nu_{lam} and Nu_{turb} are defined as follow:

(1)

(2)

Table I: Forced convective heat transfer correlations in packed beds.

Authors	Correlations	Range
Gnielinski [8]	$Nu_d = (1+1.5(1-\varepsilon))\times\left(2+\sqrt{Nu_{lam}^2+Nu_{turb}^2}\right)$	$Re_d/\varepsilon \le 2\times10^4$ $0.6 < Pr < 10^3$ $0.26 < \varepsilon < 0.935$
Wakao and Kaguei[4]	$Nu_d = 2+1.1Pr^{1/3}Re_d^{0.6}$	$20 < Re_d < 7.6\times10^3$ $0.7 < Pr < 1$
KTA [10]	$Nu_d = 1.27\left(Pr^{1/3}/\varepsilon^{1.18}\right)Re_d^{0.36} + 0.033\left(Pr^{2/3}/\varepsilon^{1.07}\right)Re_d^{0.86}$	$100 < Re_d < 10^5$ $0.36 < \varepsilon < 0.42$
Achenbach [3]	$Nu_d = [\left(1.18Re_d^{0.58}\right)^4 + \left(0.23\left(\frac{1}{1-\varepsilon}Re_d\right)^{0.75}\right)^4]^{0.25}$	$Re_d/\varepsilon < 7.7\times10^5$ $0.7 < Pr < 7$

3. Experiments

3.1 Analogy concept

The mass transfer experiments were performed using the electroplating system based on analogy concept between the heat and mass transfer. A copper sulfate–sulfuric acid ($CuSO_4$–H_2SO_4) electroplating system was adopted as the mass transfer system. The mass transfer rate was measured using the limiting current technique in electroplating system [11]. In electroplating system, the cathode simulates the heated sphere where the buoyance force is induced by the reduction of copper ions. Further details of this technique can be found in Park and Chung [12].

3.2 Test matrix and apparatus

Table II shows test matrix for forced convection in packed beds. The height was determined for a single heated sphere as H/d = 10 which is the H = 0.06 m. For all heated sphere in packed beds, the H/d is varied from 3.3 to 43.3 which corresponding to height from 0.02 m to 0.26 m. Prandtl number was fixed at 2,014. The geometries are the single heated sphere and all heated sphere in packed beds. Diameter of copper sphere is 0.006 m. The duct diameter was determined as 0.08 m. The Re_d ranges from 31 to 989 for each structure.

Table II: Test matrix for packed beds.

Structure	H/d	Pr	d (m)	D (m)	Re_d	Re_D
Single heated sphere	10	2,014	0.006	0.08	31–989	413–13,187
All heated sphere	3.3					
	10					
	25					
	43.3					

Figure 1 presents an experiment circuit of packed beds. It is a closed loop consisting of a chemical pump, a bypass system, an acryl pipe and an electromagnetic flow meter. The bypass system controls the volume flow rate which come into test section. The fluid from the reservoir pass the pump, test section and flow meter. The electric potential is applied by the power supply (SGI 100A/150V, SGI) and the current is measured by the Multimeter (FLUKE-45B+).

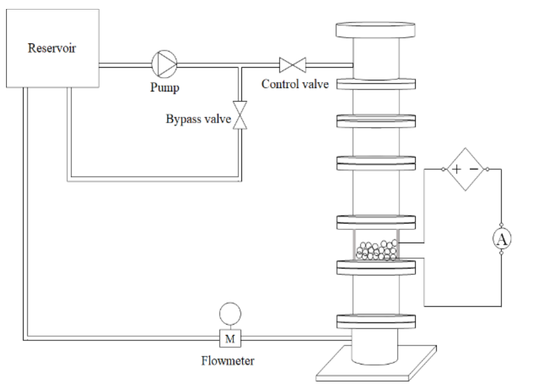
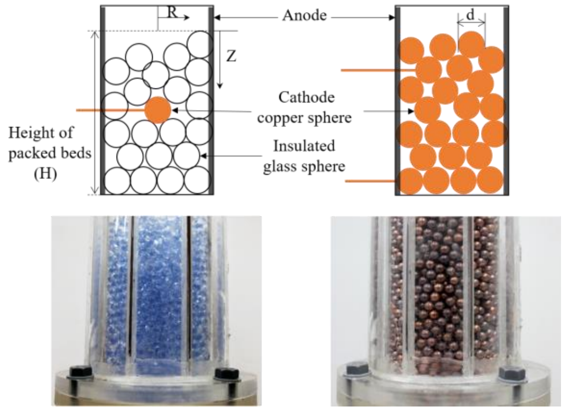


Fig. 1. Experimental circuit.

Figure 2 shows the schematics and photographs of the test sections. The test section was filled with spheres. The anodes are embedded in the furrow longitudinally on wall of test section. The depth of furrows where the anodes located is enough to separate from cathode. For single heated sphere case, the cathode copper sphere was located in insulated packed beds. All heated sphere case, the packed beds were composed of copper spheres.



(a) Single heated sphere (b) All heated sphere

Fig. 2. Schematics and photographs of the test sections.

4. Results and discussion

4.1 A single heated sphere in packed beds

Figure 3 shows the results of current experiments and existing correlations. The open symbols denote the test results of current experiments. The correlations were presented at *Pr* 0.7 for lower bound and 2,014 for upper bound.

The correlations show similar trend at *Pr* = 0.7. However, when the *Pr* is larger than 0.7, the Achenbach's [3] correlation shows lower Nu_d than other correlations. Achenbach [3] performed experimental studies for 0.7 < *Pr* < 7 and proposed correlation where the *Pr* is not a parameter in the correlation. For the correlation of Gnielinski [8], the correlation was formed by multiplying porosity factor to heat transfer correlation of single sphere. The forced convection heat transfer of single sphere in an open channel is affected by *Pr*. Therefore, the correlation of Gnielinski [8] seems to be affected by *Pr*. The other correlation were suggested based on the experiments results with *Pr* < 1. This seems that the correlations do not reflect the *Pr* effect. Therefore, the correlations show similar Nu_d at *Pr* = 0.7 and difference for larger *Pr* than 0.7.

The Nu_d increases with Re_d for all cases. The test results show good agreements with the correlation of Achenbach [3]. And the results show lower Nu_d than other correlations. As mentioned about correlation of Achenbach [3], the *Pr* is not a parameter. It seems that the heat transfer was unaffected by *Pr* due to the eddy motions, vortex flow, recirculation etc.

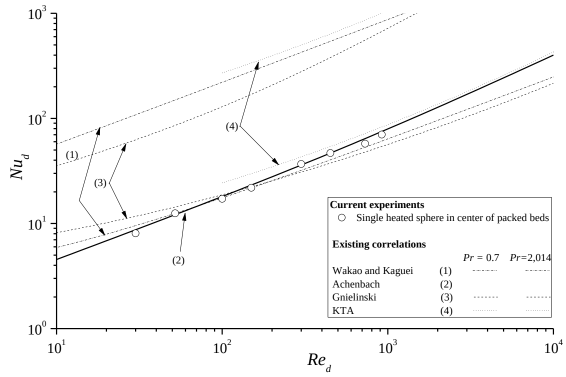


Fig. 3. Comparison test results with existing correlations.

4.2 All heated sphere in packed beds

Figure 4 shows the results of all heated sphere in packed beds varying the *H/d* from 3.3 to 43.3. The correlation of Achenbach [3] was plotted since the correlation coincide well with the results of single heated sphere in center of packed beds.

The Nu_d's decrease when the *H/d* increase for the same Re_d. This seems to be due to the preheating effect. As the *H/d* increases, the preheated upstream reduces the downstream heat transfer. Therefore, the Nu_d decrease with the increase of *H/d*. When the *H/d* decrease, the Nu_d increase due to the dispersion effect which is the several dimples of boundary layer caused by contact point.

The slope of test results decrease with increase of *H/d*. At *H/d* = 3.3, the Nu_d increase more rapidly than other results. The steep slope was formed due to the proportion of the area influenced by the fresh fluid. When the *H/d* becomes large at 43.3, the slope of Nu_d decrease due to low influence of fresh fluid. As the *H/d* increase, the proportion of area affected by fresh fluid decrease. This means the heat transfer becomes insensitive for Re_d. Therefore, the slope of Nu_d decrease with *H/d* increase.

When the *H/d* = 10, the results show good agreement with correlation. This *H/d* is similar to experiments of Achenbach. However, the heat transfer single heated sphere in unheated packed beds is different from all heated packed beds. First, the all heated sphere in packed beds influenced by preheating effect, dispersion effect, entrance effect and so on. And second, Abdulmohsin and Al-Dahhan test results show the similar Nu_d for single heated sphere in packed beds when the *H/d* is 20. Therefore, the single heated sphere in unheated packed beds is not influenced by *H/d*.

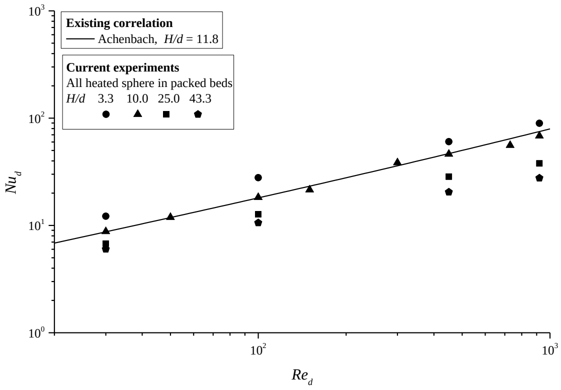


Fig. 4. Comparison test results of all heated sphere in packed beds with correlations.

5. Conclusion

This paper is to discuss the experiments results of heat transfer varying positions of a single heated sphere in unheated packed beds, and compare the single sphere correlation with all heated sphere in packed beds.

For single heated sphere in packed bed case, the single heated sphere in packed beds show good agreements with the correlation of Achenbach where the *Pr* not act as parameter. This seems that the properties do not affect the heat transfer.

For all heated sphere in packed beds, the heat transfer decreases when the height of packed beds increase. This seems to the preheating increase when the height of packed beds increase.

In this study, mass transfer experiments will replace heat transfer experiments based on analogy concept. An electroplating system is adopted using limiting current technique.

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