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Forced Convection Heat Transfer of a sphere in Packed Bed Arrangement

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1. Introduction

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

Relatively less experimental studies were performed for forced convection heat transfer in packed bed. Because it is hard to simulate all of spheres as heat sources in packed bed to measure the temperature and velocity because of complicate flow caused by random packing structure. Some experimental studies simulated as heated single sphere in unheated packed bed [3, 4] and most studies were performed numerically [1, 5, 6]. However, numerical study is restrictive because numerical method is difficult to simulate random packed bed.

This paper analysis and discuss the forced convective heat transfer from heated single sphere, which is buried in unheated packed bed, depending on Re_d with porosity. The present work determines the test matrix for the packed bed experiment. And this study discuss difference of heat transfer according to the location of heated sphere and compared heated bed with heated sphere in packed bed and compared FCC (Face Centered Cubic), HCP (Hexagonal Closed Packed) structured packed bed with random packed.

2. Background

2.1 Forced convection heat transfer in packed bed

The basic idea for treatment of pebble bed reactor heat transfer is assuming porous media. In packed bed, the dominant parameters are Re_d, ε (Porosity). The forced convection heat transfer in packed bed is proportional to Re_d. The characteristic length for Re_d is a pebble diameter.

The statistical quantity porosity ε for a randomly packed bed is defined as follow:

$$\varepsilon = 1 - \frac{V_s}{V_t} \tag{1}$$

The V_s is a volume of spheres and V_t is a total volume in a duct.

Auwerda et al. [7] reported that porosity become constant when the distance from the sphere to wall and bottom is over 6 times of sphere diameter respectively. The lower porosity at the bed center reduces the velocity of the fluid flow in this region, forcing the fluid to flow through the region of higher porosity, which is close to the bed wall [4].

The forced convection heat transfer experiments were carried out for heated single sphere located in unheated packed bed. Achenbach [2] studied the forced convection performing the heat transfer experiment using helium and the mass transfer experiment naphthalene for mass transfer, at $Re_d/\varepsilon \le 7.7 \times 10^5$ and $1 < Re_d/\varepsilon < 2.5\times10^4$ respectively and proposed empirical correlation. Abdulmohsin and Aldahhan [3] carried out experimental studies in packed bed at $5 < Re_d < 6\times10^3$. They change the heat source location vertically along the centerline, and radially at the middle elevation.

Figure 1 shows the radial profiles of convective heat transfer coefficient. The R is a bed radius, D is a bed diameter. The r is radial and axial distance from the centerline of the bed and the Z is axial distance from the top of the bed respectively. The heat transfer coefficients in the center (r/R = 0.0) are smaller than those near the wall (r/R = 0.9). This is due to the influence of the radial variations of the porosity in the bed. The porosity near the bed wall is higher than center. This porosity results in higher velocity of fluid and increases heat transfer rate. The increase of heat transfer rate at the bottom (Z/D=2.5) is due to enhancement of eddy motion in turbulence region. The inhomogeneity of the pebble arrangements plays an important role in determining the flow pattern between the pebbles, and consequently, the heat transfer.

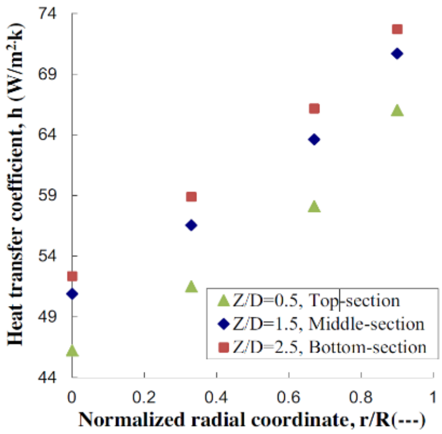


Fig. 1. Radial profiles of local heat transfer coefficients [3].

Yang et al. [8] compared heat transfer rate for random packed bed with that for structured packed bed. They reported the structured packed bed shows lower Nu_d than correlation of Wakao and Kaguei [9] for random packed bed. Ferng and Lin [5] performed numerical studies on forced convection heat transfer on BCC (Body Centered Cubic), FCC (Face Centered Cubic) structured packed bed. The calculated Nu_d is close to KTA correlation as the unit lattice stacking is piled up. Hassan [6] carried out numerical studies about pressure drop, velocity profile, and temperature distribution on the pebbles for BCC (Body Centered Cubic) structured packed bed.

2.2 Existing correlations

Several investigators carried out forced convection heat transfer experiments for single sphere in packed bed and proposed correlations. Gnielinski [10, 11] recommended the semi-empirical correlation for $Re_d/\varepsilon \leq 2\times10^4$, $0.6 < Pr < 10^4$, $0.26 < \varepsilon < 0.935$. Wakao and Kaguei [9] also proposed correlation at $20 < Re_d < 7.6\times10^3$. German nuclear safety standard commission (KTA) [12] presented correlation for $100 < Re_d < 10^5$, $0.36 < \varepsilon < 0.42$. Achenbach [2] performed heat transfer experiments for $Re_d/\varepsilon \leq 7.7\times10^5$ and mass transfer experiments for $1< Re_d/\varepsilon < 2.5\times10^4$ respectively and proposed empirical correlation. Table I summarized the correlations of investigators. In Table I, Nu_{lam} and Nu_{turb} are defined as

(2)

(3)

Table I: Forced convection heat transfer correlations in packed bed.

Authors	Correlations	Range
Gnielinski [10, 11]	$Nu_d = (1+1.5(1-\varepsilon))\times \left(2+\sqrt{Nu_{lam}^2+Nu_{turb}^2}\right)$	$Re_d/\varepsilon \leq 2\times10^4$ $0.6 < Pr < 10^4$ $0.26 < \varepsilon < 0.935$
Wakao and Kaguei[9]	$Nu_d = 2+1.1Pr^{1/3}Re_d^{0.6}$	$20 < Re_d < 7.6\times10^3$
KTA [12]	$Nu_d = 1.27\left(\frac{Pr^{1/3}}{\varepsilon^{1.18}}\right)Re_d^{0.36} + 0.033\left(\frac{Pr^{2/3}}{\varepsilon^{1.07}}\right)Re_d^{0.86}$	$100 < Re_d < 10^5$ $0.36 < \varepsilon < 0.42$
Achenbach [2]	$Nu_d = [(1.18Re_d^{0.58})^4 + \left(0.23\left(\frac{1}{1-\varepsilon}Re_d\right)^{0.75}\right)^4]^{0.25}$	$Re_d/\varepsilon < 7.7\times10^5$

Figure 2 shows the existing correlations depending on Re_d. Nu_d is proportional to Re_d. At $Re_d < 10^2$, the correlation of Gnielinski [10, 11] shows higher Nu_d than that of Achenbach [2]. And all existing correlations are similar in range of $10^2 < Re_d < 10^4$.

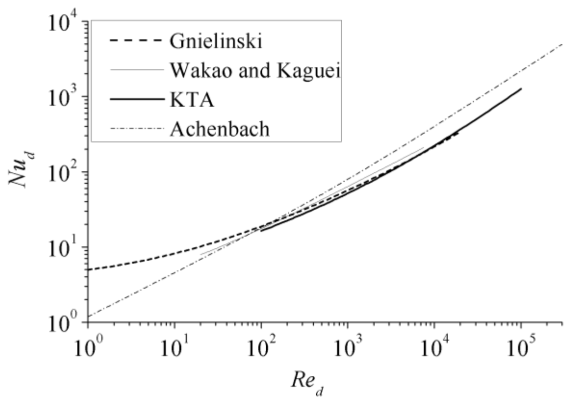


Fig. 2. Comparison existing correlations.

3. Experiments

3.1 Analogy concept

Based on analogy concept, the mass transfer experiments replaced heat transfer experiments. In electroplating system, mass transfer rate was measured by the limiting current technique with a copper sulfate–sulfuric acid ($CuSO_4$–H_2SO_4) [13]. In electroplating system, the cathode simulates the heated wall where the buoyancy is induced by the reduction of copper ions. Further details of the limiting current technique can be found in Park and Chung [14].

3.2 Test matrix and apparatus

Table II shows test matrix. Prandtl number was fixed 1,965. The packing structures are single sphere in packed bed, random, and structured packed bed (FCC, HCP). Diameter of copper sphere is 0.006 m. As porosity become constant when the distance from pebble to the wall and bottom more than 6 times of pebble diameter respectively, duct diameter D was determined as 0.08 m, which is more than 13 times of sphere diameter. The height was determined as 0.04 m which is more than 6 times of sphere diameter. In order to compare heat transfer rate according to location of heat source, the sphere was located at top, middle, bottom of the bed where the distance from the bottom at is 1, 3 and 6 times of sphere diameter respectively. At each height, the distance from the bed wall is 1, 3, 7 times of sphere diameter distance from the bed wall to compare each heat transfer rate for each location, and to compare averaged heat transfer for each locations with heated bed. The porosity was assumed as 0.39 at random structure, and it is 0.26 for FCC and HCP structure. The Re_d ranges from 20 to 1,300 for each structure.

Table II: Test matrix.

Pr	Structure	d (m)	D (m)	Re_d	Re_D
1,965	Single Random FCC, HCP	0.006	0.08	20 – 1,300	300– 17,000

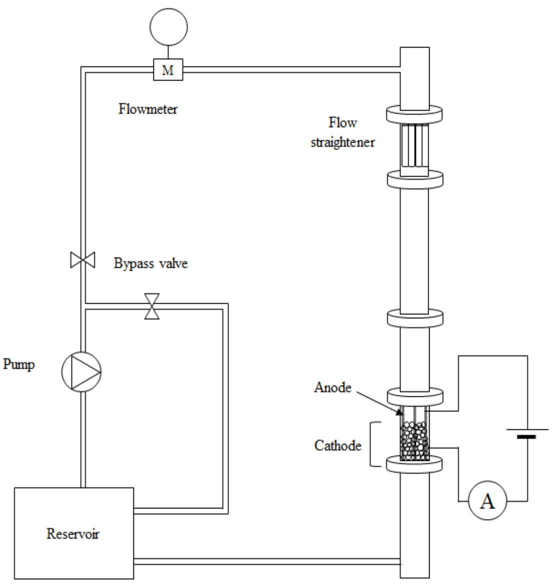


Fig. 3. A schematic of the test apparatus.

Figure 3 shows an experiment circuit of packed bed. It is a closed loop consisting of an acryl pipe, a chemical pump, an electromagnetic flow meter and a bypass system. The bypass system controls the mass flow rate which come into test section. A flow straightener was installed at the unheated section to achieve fully developed condition. The fluid from the reservoir pass the pump, flow meter and test section. A cathode was located in acrylic duct. The electric potential is applied by the power supply (VüPOWER K1810) and the current is measured by the Multimeter (FLUKE-45B+).

Figure 4 shows the test section with top view. The test section was filled with spheres. The anodes are located in test section wall where the hollowed out longitudinally. The depth of furrows where the anodes located is enough to separate from cathode.

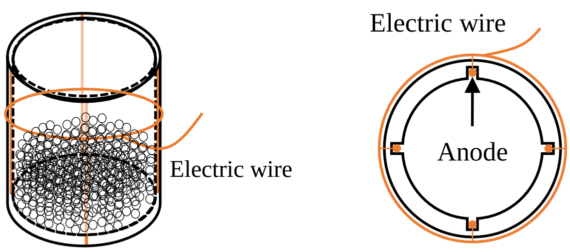
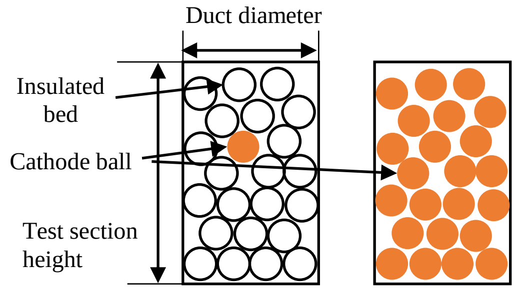


Fig. 4. Test section and top views.

Figure 5 shows the side view of test section. In Fig. 5 (a), the cathode copper ball is located in insulated packed bed. The Fig. 5 (b) represents the packed bed which is full of cathode copper ball



(a) Single sphere in packed bed (b) Packed bed

Fig. 5. The side view of test section.

4. Analysis

For heated single sphere in unheated packed bed, Nu_d increase as the sphere is close to the wall because of increasing porosity. And also increasing Nu_d increase as sphere approach the bottom because of enhancing eddy motion.

Existing experimental studies performed as heated sphere in packed bed mostly. However this method did not considered preheating effect. This effect decreased heat transfer rate on downstream in packed bed.

The flow in structured packed bed can be analyzed as unit lattice. However, the flow in random packed bed which is irregular structure, is hard to construct for unit lattice. This irregular structure cause the complicated flow and different heat transfer rate.

5. Conclusion

This paper is to discuss and make the plan to experiment the heat transfer for depending on location of heated single sphere in unheated packed bed, to compare single sphere in packed bed with heated packed bed and to compare the structured packed bed with random packed bed.

The Nu_d increase as heated single sphere is close to the wall and bottom because of increasing porosity and enhancing eddy motion respectively.

The existing experiment of heated sphere in packed bed do not consider the preheating effect which decrease heat transfer on downstream.

The heat transfer rate of structured packed bed is different from random packed bed because of unsteady flow in random packed bed.

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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REFERENCES

[1] J. J. Lee et al., Numerical Treatment of Pebble Contact in the Flow and Heat Transfer Analysis of a Pebble Bed Reactor Core, Nuclear Engineering and Design, Vol. 237, pp. 2183-2196, 2007.

[2] G. C. Park et al., Study on multidimensional temperature and flow field in pebble core, KAERI-Preliminary Conceptual Design and Development of Core Technology of Very High Temperature Gas-Cooled Reactor for Hydrogen Production, Korea, 2006.

[3] E. Achenbach, Heat and Flow Characteristics of Packed beds, Experimental Thermal and Fluid Science, Vol. 10, pp. 17-27, 1995.

[4] R. S. Abdulmohsin, M. H. Al-Dahhan, Characteristics of Convective Heat Transport in a Packed Pebble-bed Reactor, Nuclear Engineering and Design, Vol. 284, pp. 143-152, 2015.

[5] Y. M Ferng, K. Y. Lin, Investigating Effects of BCC and FC Arrangements on Flow and Heat Transfer Characteristics in Pebbles through CFD Methodology, Nuclear Engineering Design, Vol. 258, pp. 66-75, 2013.

[6] Y. A. Hassan, LES Simulation in Pebble Bed Gas Cooled Core Reactors, Nuclear Engineering Design, Vol.2389, pp. 530-537, 2008.

[7] G. J. Auwerda et al., Comparison of Experiments and Calculations of Void Fraction Distributions in Randomly Stacked Pebble Beds, Advances in Reactor Physics to Power the Nuclear Renaissance (PHYSOR), Pennsylvania, 2010.

[8] Jian Yang et al. Experimental analysis of forced convective heat transfer in novel structured packed beds of particles, Chemical Engineering Science, Vol. 71, pp. 126-137, 2012.

[9] N. Wakao, S. Kaguei, Heat and Mass Transfer in Packed Bed, 1st ed. Gordon and Breach Science Publishers, New York.

[10] V. Gnielinski, Formula for Calculating the Heat and Mass Transfer in through Flow of a Fixed Bed at Medium and Large Peclet. Process Technology, Vol. 12, pp. 63-366, 1978.

[11] V. Gnielinski, Equations for Calculation of Heat and Mass Transfer during Flow through Stationary Spherical Packing at Moderate and High Peclet Numbers, International Chemical Engineering, Vol. 21, pp. 378-383.

[12] Nuclear Safety Standard Commission (KTA), KTA 3102.2 Reactor Core Design of High-Temperature Gas-Cooled Reactors, Part 2: Heat Transfer in Spherical Fuel Elements, 1983.

[13] S. H. Ko, D. W. Moon, B. J. Chung, Applications of electroplating method for heat transfer studies using analogy concept, Nuclear Engineering and Technology, Vol. 38, pp. 251-258, 2006.

[14] H.K. Park, B.J. Chung, Mass Transfer Experiments for the Heat Load during In-Vessel Retention of Core Melt, Nuclear Engineering and Technology, DOI: 10.1016/j.net.2016.02.015.