*Transactions of the Korean Nuclear Society Spring Meeting*
*Jeju, Korea, May 19-20, 2022*

# Forced convection heat transfer of the heating packed bed varying the sphere diameter and bed height

Je-Young Moon[a,b], Bum-Jin Chung[a*]
[a]*Department of Nuclear Engineering, Kyung Hee University, 1732 Deogyeong-daero, Giheung-gu, Yongin-si, Gyeonggi-do, 17104, Korea*
[b]*Thermal Hydraulic Safety Research Division, Korea Atomic Energy Research Institute, 111 Daedeok-daero 989 beon-gil, Yuseong-gu, Daejeon, 34057, Korea*
[*]*Corresponding author: bjchung@khu.ac.kr*

## 1. Introduction

Packed bed has been adopted in many engineering applications such as the pebble fuel of nuclear reactors [1-4], thermal energy storage (TES) system [5], debris bed in a severe accident of a nuclear power plant [6], etc. [7-10].

As the performance of various applications is determined by the convective heat transfer in the packed bed, many studies have been conducted over the past few decades [11,12]. As the ranges of engineering applications are wide, the ranges of major parameters of the existing studies are scattered and sometimes the results do not coincide. Moreover, it is hard to simulate the uniformly heated condition for all sphere, although the inductive heating technique is successfully adopted in most recent studies [4].

This study investigated the influence of sphere diameter ($d$) and bed height ($H$) on the forced convective heat transfer of the heating 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 $Sc$ corresponding to the $Pr$ was 2,014. The sphere diameter ($d$) was 0.004 and 0.010 m. The bed diameter ($D$) was fixed to 0.06 m. The ratios of bed height to sphere diameter ($H/d$) were also changed from 5 to 20 for $d = 0.004$, 0.010 m and from 5 to 30 for $d = 0.006$ m. The superficial velocity ($u_s$) was varied from 0.01 to 0.56 m/s, which correspond to the $Re_{dh}$ of 13–5,409.

## 2. Theoretical backgrounds

Meng et al. [13] conducted the experiments on the pebble bed heat transfers varying the sphere diameter ($d$). They used the oxidized stainless steel spheres of $d = 0.003$, 0.008 m and carbon steel spheres of $d = 0.008$ m. The diameter ($D$) and height ($H$) of packed bed were 0.075 m and 0.670 m, respectively. They reported that the measured heat transfer coefficients for $d = 0.003$ m were higher than those for $d = 0.008$ m. This difference increased as the $Re_{dh}$ increased. It was because the total heating surface in the pebble bed increased with decrease of sphere diameter ($d$).

Liu et al. [3] researched the convective heat transfer in the Fluoride-salt-cooled High-temperature Reactors (FHRs). The Downtherm A was used as the simulant fluid for the FLiBe, which corresponded to $Pr$ of 14–19. The $Re_{dh}$ ranged from 90 to 2,500. Also, the bed to sphere diameter ratio ($D/d$) was varied to 8–10. As the $Re_{dh}$ increased, the average $Nu_{dh}$'s increased. They also mentioned that the average $Nu_{dh}$ increased with decreasing sphere diameter ($d$) as it caused the decrease of porosity resulting the increase of the pore velocity.

Liu et al. [4] performed the experiments for a pebble bed to investigate the Water-cooled Pebble Bed Reactor (WPBR). The $Pr$ was varied to 2.3–5.9. The range of $Re_{dh}$ was from 350 to 9,000. The sphere diameter ($d$) was 0.008 and 0.010 m, and the bed to sphere diameter ratios ($D/d$) were 8.5 and 10.625. Liu et al. [4] reported that the heat transfer enhanced when the sphere diameter ($d$) decreased, because the low porosity caused the large pore tortuosity in the pebble bed and the increase of flow velocity inside the bed at the same $Re_{dh}$.

## 3. Experiments

### 3.1 Experimental Method

Heat and mass transfer systems are analogous as their governing equations for each system are mathematically the same. Therefore, by the mass transfer experiments, the heat transfer problems can be solved effectively [14].

In this study, a $CuSO_4$-$H_2SO_4$ electroplating system was adopted as the mass transfer system. In order to calculate the mass transfer coefficient ($h_m$), we used the limiting current technique [15]. Thus, the $h_m$ 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 [16].

This technique has been developed by several researchers and are well-established as an experimental methodology [17-21].

### 3.2 Test matrix

Table I shows the test matrix of forced convection experiments on the heating packed bed. The sphere diameter (*d*) was 0.004 and 0.010 m. The bed diameter (*D*) was fixed to 0.06 m. Thus, the bed to sphere diameter ratios (*D*/*d*) were changed to 15, 10 and 6 respectively. Also, the bed height (*H*) varied to 0.02–0.08 m for *d* = 0.004 m, 0.03–0.18 m for *d* = 0.006 m and 0.05–0.20 m for *d* = 0.010 m respectively. The ratio of bed height to sphere diameter (*H*/*d*) was changed to 5–20 for *d* = 0.004, 0.010 m and 5–30 for *d* = 0.006 m. The range of superficial velocity ($u_s$) was from 0.01 to 0.56 m/s corresponding to the $Re_{dh}$ of 13–5,409. The Sc corresponding to *Pr* was 2,014, which depended on the concentrations of $CuSO_4$ (0.05 M) and $H_2SO_4$ (1.5 M). The average porosity for each packed bed in this study was measured from 0.408 to 0.442.

Table I: Test matrix.

| ***Sc*** | ***D* (m)** | ***d* (m)** | ***H* (m)** | $Re_{dh}$ |
|---|---|---|---|---|
| 2,014 | 0.06 | 0.004 | 0.02, 0.04, 0.08 | 13–3,050 |
| | | 0.006 | 0.03, 0.06, 0.12, 0.18 | 20–5,004 |
| | | 0.010 | 0.05, 0.10, 0.20 | 36–5,409 |

### *3.3 Experimental apparatus*

Figures 1 and 2 present the schematic circuit and the photographs of the test sections for the forced convection experiments. In Fig. 1, the flow from a reservoir passed through a magnetic pump (PM-753PI, WILO), test section, and then returned back to the reservoir. Thus, the flow direction is upward. The flow rate was controlled by control and bypass valves and measured using an electromagnetic flowmeter (LF600, Toshiba). The copper spheres acted as the cathode simulating the heating spheres. The copper anode rods were embedded at the inner wall of the duct and the additional copper anode pipes were also located at the upper and lower parts of the test section. In order to eliminate the inlet and outlet effects in the packed bed, the glass spheres of 5–7 layers were respectively stacked at the top and bottom of the test section [3,22]. In Fig. 2, several copper rods connecting with the copper spheres were penetrated into the acryl duct to apply the stable electric potential through the point contacts among copper spheres. The rod thickness was 0.002 m for *d* = 0.004 m and 0.003 m for *d* = 0.006, 0.010 m. Also, a permeable grid was installed on the top and bottom of the test section. The electrical potential was applied by a power supply (N8952A, Keysight) and the electric current was measured using the DAQ (NI-9227 & cDAQ-9179, National Instruments) system and LabVIEW.

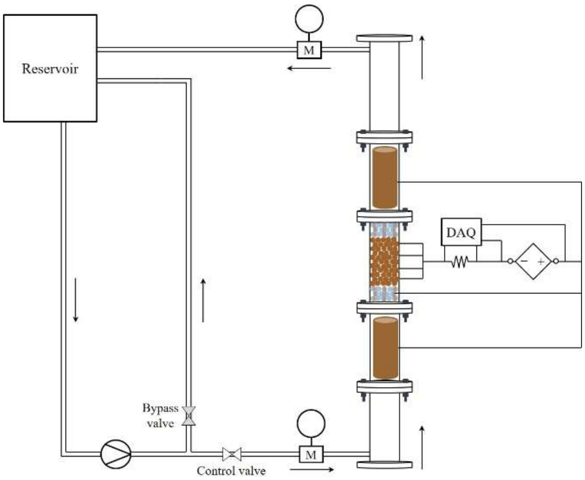
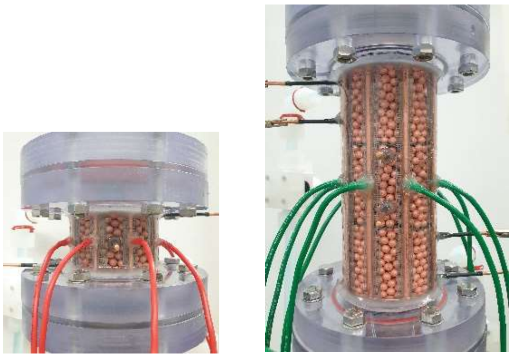


Fig. 1. Schematic of the test facility for forced convection experiments.



(a) *H* = 0.06m (b) *H* = 0.18 m

Fig. 2. Photographs of the test section varying the bed height (*H*) for *d* = 0.006 m.

## 4. Results and discussion

### *4.1 Transition to the turbulent flow in the packed bed*

For the forced convective flow, it is important to determine the transition criterion to turbulent flow regime as the mechanism of heat transfer in a packed bed can differ according to the flow regime. The transition criterion from the transitional flow to the turbulent flow is unclear in the packed bed due to the strong uncertainty of the phenomena for the packed bed. It could be caused by the complicated phenomena of the packed bed and the difference of bed geometry, fluid characteristics, etc.

Figure 3 shows the measured $Nu_{dh}$ for *H*/*d* = 5 with respect to $Re_{dh}$. Based on the points predicted to the transition, the measured data were grouped to transitional and turbulent flows, and then this process was repeated until the slope difference was largest. Thus, the lines intersected at $300 < Re_{dh} < 400$, where the transition to turbulent flow regime occurred. This study concluded that the transition criterion to turbulent was $Re_{dh} \sim 400$. Similarly, Liu et al. [4] reported that the transition to turbulent occurred at $Re_{dh} \sim 270$.

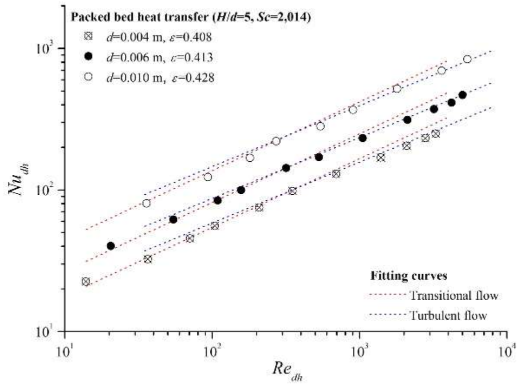


Fig. 3. Transition criteria of the forced convective flow in the packed bed.

### *4.2 Influence of sphere diameter, bed height and flow velocity on the heat transfer of the packed bed*

Figure 4 compares the measured heat transfers of this study with the existing correlations of a heating packed bed for $d$ = 0.006 m. In Fig. 4, the $Nu_{dh}$'s from the existing studies are widely scattered and the slope of the existing correlations are different. It means that the heat transfer characteristics in the heating packed bed are complex and depend on various parameters. Other sphere diameters of this study showed the similar results.

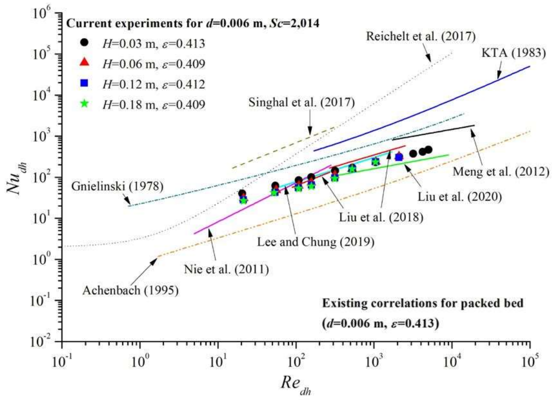


Fig. 4. Comparison of measured $Nu_{dh}$'s of this study with existing correlations for the packed bed ($d$=0.010 m).

Figure 5 presents the $Nu_{dh}$ values of the heating packed bed according to the $Re_{dh}$ for various sphere diameters ($d$) and bed heights ($H$). For all cases, the measured data increased with the increase of $Re_{dh}$. As aforementioned, the difference of $Nu_{dh}$ slope was observed in Fig. 5. The laminar wake and oscillation in the transitional flow ($13 \leq Re_{dh} \leq 400$) and the flow mixing in the turbulent flow ($400 < Re_{dh} \leq 5{,}409$) affected the forced convective heat transfer in the packed bed.

In Fig. 5, The influence of bed height ($H$) on the packed bed heat transfer differed in each flow regime. For the low $Re_{dh}$, the heat transfer impaired with the increase of bed height ($H$). However, the $Nu_{dh}$ for the high $Re_{dh}$ was unaffected by the bed height ($H$). It was due to the competition between preheating and flow mixing effects. For the transitional flow, the preheating causes the impairment of heat transfer and the laminar wake motion by the packed bed structure leads to the enhancement of heat transfer. However the mild flow mixing in the transitional flow quickly dissipates owing to the deficiency of continuous energy transport. Thus, in this regime, the preheating becomes dominant.

For the turbulent flow regime, the preheating occurs like the transitional flow. However, the intensified eddy motion and chaotic vortex by the high velocity causes the enhancement of momentum transport, and hence the strong turbulent mixing eventually countervails the preheating.

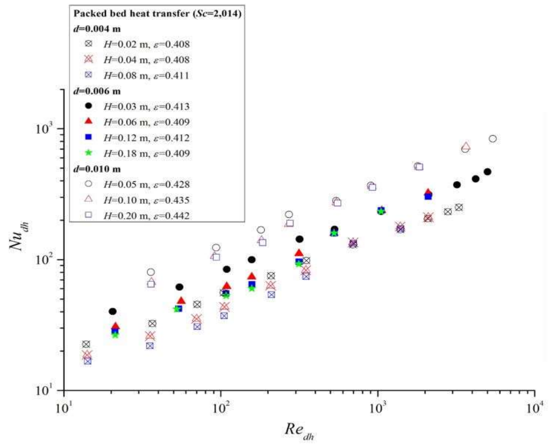


Fig. 5. Measured $Nu_{dh}$'s according to $Re_{dh}$ for various sphere diameters ($d$) and bed heights ($H$) of a packed bed.

Figure 6 shows the measured mass transfer coefficient ($h_m$) according to the flow velocity for $d$ = 0.006 m and $H/d$ = 10. The mass transfer coefficient ($h_m$) decreased with the decrease of sphere diameter ($d$) regardless of the $H/d$. When the sphere diameter ($d$) is small, the pore size in the packed bed decreases. It leads to the formation of complex flow paths inside the bed, and hence the stagnant and recirculation flows occur. Also, for small $d$, the heating surface to pore volume ratio increases due to the decrease of pore size. Thus, the cooling performance of packed beds is impaired.

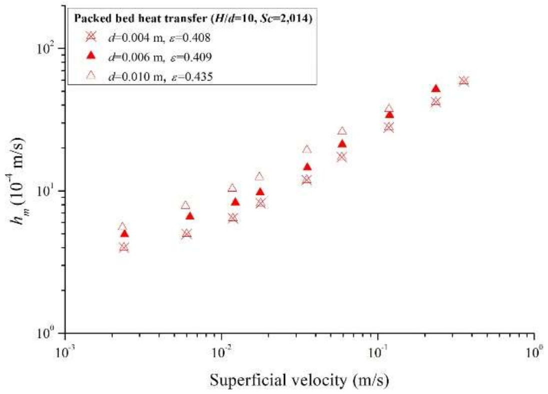


Fig. 6. Measured $h_m$'s according to the flow velocity for $d$ = 0.006 m and $H/d$ = 10.

## 4. Conclusions

The influences of sphere diameter and bed height on the forced convective heat transfer of all heating spheres in the packed bed were investigated. Mass transfer experiments using the $CuSO_4$-$H_2SO_4$ electroplating system were performed based upon the analogy between heat and mass transfers.

The comparison of the experimental results with the existing correlations revealed that the existing heat transfer correlations are scattered in their experimental ranges and the experimental results as well. The $Nu_{dh}$ trends with respect to $Re_{dh}$ were mostly similar.

The overall heat transfer of the packed bed was enhanced by the increase of the flow velocity, which also meant the transition to the turbulent flow. This study discovered that the transition to the turbulent flow occurred at $Re_{dh} \sim 400$.

The average heat transfer of the packed bed was impaired with the increase of the bed height due to the preheating, which clearly confirmed under the transitional flow regime. However, the packed bed heat transfer for the turbulent flow was unaffected by the bed height due to the enhanced mixing by the intensified eddy motion. When the sphere diameter decreased, the bypass flow effect at the near wall in the packed bed became pronounced by the decrease of the pore volume, and hence it caused the impairment of the cooling performance of the packed bed.

## REFERENCES

[1] R.S. Abdulmohsin and 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.

[2] A. Koster, H.D. Matzner and D.R. Nicholsi, PBMR design for the future, Nuclear Engineering and Design, Vol. 222, pp. 231–245, 2003.

[3] L. Liu, D. Zhang, L. Li, Y. Yang, C. Wang, S. Qiu and G.H. Su, Experimental investigation of flow and convective heat transfer on a high-Prandtl-number fluid through the nuclear reactor pebble bed core, Applied Thermal Engineering, Vol. 145, pp. 48–57, 2018.

[4] L. Liu, J. Deng, D. Zhang, C. Wang, S. Qiu, G.H. Su, Experimental analysis of flow and convective heat transfer in the water-cooled packed pebble bed nuclear reactor core, Progress in Nuclear Energy, Vol. 122, 103298, 2020.

[5] T. Esence, A. Bruch, S. Molina, B. Stutz, J.F. Fourmigué, A review on experience feedback and numerical modeling of packed-bed thermal energy storage systems, Solar Energy, Vol. 153, pp. 628–654, 2017.

[6] J.H. Park, Modeling of Two-Phase Flow Pressure Drop for Predicting Ex-Vessel Debris Bed Coolability in Nuclear Reactor Severe Accident, Ph.D. thesis, Pohang University of Science and Technology, Korea, 2018.

[7] I. Sarbu, C. Sebarchievici, Solar Heating and Cooling Systems, Academic Press, Cambridge, England, 2017, pp. 99–138.

[8] B. Yaron, R. Calvet, R. Prost, Soil Pollution, first ed., Springer, Heidelberg, Germany, 1996, pp. 3–4.

[9] J. Yang, D.Y. Lee, S. Miwa, S. Chen, Overview of filtered containment venting system in Nuclear Power Plants in Asia, Annals of Nuclear Energy, Vol. 119, pp. 87–97, 2018.

[10] K.J. Albrecht, C.K. Ho, Heat Transfer Models of Moving Packed-Bed Particle-to-$SCO_2$ Heat Exchangers, Proceedings of the ASME 2017 Power and Energy Conference (PowerEnergy 2017), Charlotte, North Carolina, USA, 25–30 June, 2017.

[11] D.S. Wen and Y.L. Ding, Heat transfer of gas flow through a packed bed, Chemical Engineering Science, Vol. 61, pp. 3532–3542, 2006.

[12] A. Singhal, S. Cloete, S. Radl, R. Quinta-Ferreira and S. Amini, Heat transfer to a gas from densely packed beds of monodisperse spherical particles, Chemical Engineering Journal, Vol. 314, pp. 27–37, 2017.

[13] X. Meng, Z. Sun, G. Xu, Single-phase convection heat transfer characteristics of pebble-bed channels with internal heat generation, Nuclear Engineering and Design, Vol. 252, pp. 121–127, 2012.

[14] A. Bejan, Convection Heat Transfer, fourth ed., Wiley, New York, 2013, pp. 501–504, 537–595.

[15] E.J. Fenech, C.W. Tobias, Mass transfer by free convection at horizontal electrodes, Electrochimica Acta, Vol. 2, pp. 311–325, 1960.

[16] D.Y Lee, M.S. Chae, and B.J. Chung, Natural convective heat transfer of heated packed beds, International Communications in Heat and Mass Transfer, Vol. 88, pp. 54–62, 2017.

[17] J.N. Agar, Diffusion and convection at electrodes, Discussion of the Faraday Society, Vol. 1, pp. 26–37, 1947.

[18] C.W. Tobias, R.G. Hickman, Ionic mass transfer by combined free and forced convection, Z. Phys. Chem., Vol. 2290, pp. 145–166, 1965.

[19] 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.

[20] M.S. Chae, B.J. Chung, Natural convection heat transfer in a uniformly heated horizontal pipe, Heat Mass Transfer 50 (2014) 115–123.

[21] B.J. Chung, M.S. Chae, J.Y. Moon, H.K. Park, Review of research using analogy concept for thermal hydraulic and severe accident experiments, Nuclear Engineering and Design, Vol. 379, 111257, 2021.

[22] J.Y. Moon, S.I. Baek, B.J. Chung, Influence of position on the natural and forced convective heat transfer of a single heating sphere in a packed bed, Experimental Thermal and Fluid Science, Vol. 132, 110549, 2022.