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Experimental Analysis of Stagnant Effective Thermal Conductivity in Packed Beds: Bulk Region and Near Wall Region

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Effective thermal conductivities in four different packed beds are experimentally studied in this paper, namely two random graphite packed beds with porosity ε=0.40 and ε=0.35, a simple cubic (SC) graphite packed bed and a random stainless steel packed bed. It is found that the effective thermal conductivity of all packed beds has a downward trend as the wall is approached. Based on the effective thermal conductivity distributions, the near wall region can be defined within four pebble diameters from walls for random packed beds and one pebble diameter for SC packed beds. As a result of wall effect, the effective thermal conductivities in the near wall regions are generally smaller than those in the bulk regions at the same temperature. It is found that the ZBS correlation gives best predictions in bulk regions and in near wall regions with the proper empirical parameter selected.

1. Introduction

Based on the large surface area to volume ratio, packed beds have excellent performance in heat transfer and mass transfer and are widely used in nuclear reactors (Bu et al., 2017), adsorption process (Haddadi et al., 2016), magnetic refrigeration (Shi et al., 2018) and chemical combustion process (Diglio et al., 2017). Understanding heat transfer in packed beds is essential to the design and operation of industrial packed bed applications. The heat transfer in a packed bed is complicated and then the heat transfer mechanisms are usually lumped into an important parameter called the effective thermal conductivity.

The effective thermal conductivity is dominated by the fluid and solid phase thermal conductivities as well as the microstructure of packed bed. The microstructure of a packed bed is heterogeneous and the local porosity varies sharply, especially near a wall since there the geometry of the packing is altered (Van Antwerpen et al., 2010). This is called wall effect, mainly caused by the relatively high void fraction near the wall. So the wall effect on hydrodynamic, heat and mass transfer performances for a packed bed is significant. The effective thermal conductivity is also affected by the wall effect (Dixon, 2012). Therefore, the effective thermal conductivity in the near wall region and bulk region of a packed bed would be different. The effective thermal conductivity in the bulk region has been widely studied, and some correlations were proposed, such as correlations by Zehner and Schlünder (ZS) (1970), Bauer and Schlünder (ZBS) (1978), and Hsu et al. (1995). Some of these correlations were found to be limited for the prediction of the effective thermal conductivity in the near wall region. For example, Van Antwerpen et al. (2012) found the IAEA ZS correlation and the ZBS correlation to overpredict the heat transfer in the near wall region and then presented a new model to better predict the effective thermal conductivity in the near wall region. measured and studied The local effective thermal conductivity distributions in a packed bed were studied experimentally (De Beer et al., 2018) and numerically (De Beer et al., 2017) and they found an obvious decrease in the magnitude of the effective thermal conductivity in the near wall region. In the previous work, the bulk effective thermal conductivities were consistently greater than the near-wall effective

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thermal conductivities at the same temperature (Bu et al., 2020a). The natural convection was also found to playe a contrary part in the near wall region and the bulk region (Bu et al., 2020b).
Based on the above analysis, the effective thermal conductivity in packed beds, especially in the near wall region should be discussed more to gain a better prediction of thermal behavior of a packed bed. Therefore, the effective thermal conductivities in four different packed beds, namely two random graphite packed beds with porosity ε=0.40 and ε=0.35, a simple cubic (SC) graphite packed bed and a random stainless steel packed bed, are experimentally studied in the present paper. The effective thermal conductivity distributions are analyzed in detail. Meanwhile, the experimental results in bulk regions and near wall regions are separately compared with three semi-empirical correlations.

2. Experimental system

As shown in Figure 1, the experimental system consists of six parts: a test section, a nitrogen supply, an evacuation pump, an electricity heater, a cooling loop, and a temperature data acquisition system. In the test section, pebbles are packed in a graphite box. The heater is located on the left side of the test section to heat the packed bed. A DC power supply (precision within ±0.01 V) is used to regulate power supply. A water jacket is placed on the right side of the test section to cool the packed bed. An electromagnetic flow meter (precision within ±0.5 %) is used to measure the flow rate of cooling water in water jacket. The inlet and outlet temperatures of cooling water in water jacket are monitored by two thermocouples (precision within ±0.5 K). The fluid filling in the pores of packed beds is nitrogen. The evacuation pump is used to extract the air out of the bed before charging nitrogen. The measured data including temperatures and the input power are collected by the NI data acquisition card.

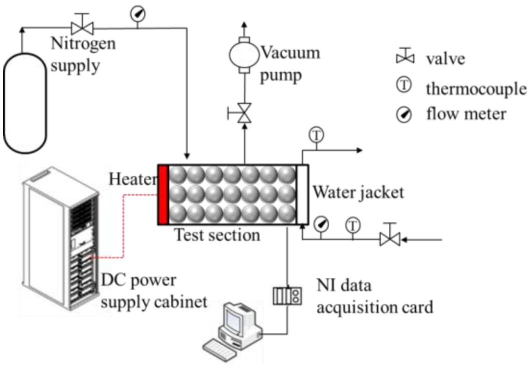

Figure 1: Schematic representation of the experimental system

Pebbles fit into a rectangular box made of graphite in the test section. The length of the graphite box is 210 mm and the width and height are both 90 mm. Four different packed beds are built, namely a random graphite packed bed with porosity ε=0.40, a random graphite packed bed with porosity ε=0.35, a SC graphite packed bed and a random 304 stainless steel packed bed (SS packed bed) with porosity ε=0.39.
As shown in Figure 2, the hot wall of the test section heated by the heater is on one side and the cold wall cooled by the flowing water is on the other side. The other sides of the test section are wrapped with the insulated materials. Accordingly, the heat flow passes through the heater, the hot wall, the pebble bed, the cold wall, and is finally taken out by the cooling water in the water jacket. Some type K thermocouples (1.5 mm diameter, precision within ±0.5 K) are inserted into the selected pebbles to measure the temperature distribution along the heat transfer direction (z-coordinate direction). There are 12 and 7 internal pebbles equipped with thermocouples for the random packed beds and the SC packed bed (see Figure 2). Thermocouples are fixed by passing through a series of holes of pebbles to minimize the disruption to the packing structure of the bed. Another two thermocouples (precision within ±0.5 K) are installed to measure the hot wall and cold wall temperature. The insulated walls and several pebbles adjacent to insulated pebbles are also equipped with thermocouples to estimate the heat loss through the insulated walls.
As shown in Table 1, five experimental tests are carried out for each packed bed. T_{hot} is the hot wall temperature and T_{cold} is the cold wall temperature. For each test, the input power and temperature are monitored until it reaches the steady state. The Fourier's law of one-dimensional heat conduction is used to calculate the effective thermal conductivity using the following equation:

$$Q(z) = -Ak_e(z)\frac{\Delta T}{\Delta z} \quad (1)$$

So the calculation of the effective thermal conductivity needs the value of the heat transfer area A, the temperature gradient, $\Delta T/\Delta z$ and the heat transfer rate $Q(z)$. The temperature gradient is obtained by the derivation of fitting curves of the measured temperatures.The detailed data reduction and the uncertainty analysis are according to the previous work (Bu et al., 2020a).

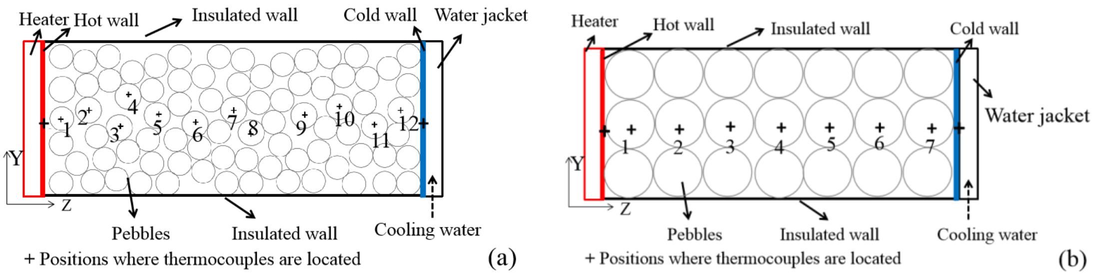

Figure 2: Schematic representation of a vertical section of test sections: (a) random graphite packed bed and (b) SC graphite packed bed

Table 1: Tests for four different packed beds

Number	T_{hot}, [K]	T_{cold}, [K]	Packed bed	Number	T_{hot}, [K]	T_{cold}, [K]	Packed bed
Case 1	378.0	307.6	random	Case 1	378.0	301.8	random
Case 2	483.0	336.7	graphite	Case 2	483.0	327.3	graphite
Case 3	583.0	370.8	d_p=15mm	Case 3	583.0	354.1	d_p=15mm
Case 4	708.0	410.6	ε=0.40	Case 4	708.0	412.5	ε=0.35
Case 5	803.0	440.2		Case 5	803.0	442.0	
Case 1	378.0	291.0	SC	Case 1	378.0	307.6	random
Case 2	484.8	316.7	graphite	Case 2	483.0	336.7	stainless
Case 3	591.0	338.0	d_p=30 mm	Case 3	583.0	370.8	steel
Case 4	705.0	355.0	ε=0.48	Case 4	708.0	410.6	d_p=15mm
Case 5	809.0	413.6		Case 5	803.0	440.2	ε=0.40

3. Experimental results and discussion

3.1 Definitions of the near wall region and bulk region

The local effective thermal conductivity distributions of the two random graphite packed beds with different packing porosity (0.40 and 0.35) are shown in Figure 3a and Figure 3b. The local effective thermal conductivity at the same position decreases as the temperatures rise (from Case 1 to Case 5) for both the random packed beds. The reason is that the heat mainly transfers through the internal pebble conduction and contact conduction. The graphite thermal conductivity decreases with the increasing temperature. The near wall region could be recognized on the basis of the effective thermal conductivity distributions. The local effective thermal conductivity begins to drop at a distance about four pebble diameters (4 d_p) from the cold wall for both random graphite packed beds. Symmetrically, the local effective thermal conductivity also has a downward trend within a distance about 4 d_p from hot wall. Overall, the near wall region can be defined within 4 d_p from walls.

The local effective thermal conductivity distributions in the SC packed bed of graphite pebbles are shown in Figure 3c. Similarly to the random packed beds, it has a downward trend near the cold wall and the hot wall. At a distance about one pebble diameter (1 d_p) from cold wall, the local effective thermal conductivity begins to drop. The local effective thermal conductivity increases more rapidly at a distance about 1 d_p from hot wall when compared to that at the middle positions of the bed. Compared to the random packed bed, wall effect in SC packed bed seems to be weaker, because the near wall region in the SC packed bed is within 1 d_p distance while for the random packed bed within 4 d_p distances.

The effective thermal conductivity distributions in the random packed bed of stainless steel pebbles are shown in Figure 3d. Contrary to the graphite packed beds, the effective thermal conductivity at the same position increases as temperatures rise (from Case 1 to Case 5) because the stainless steel and nitrogen thermal conductivities both increase with increasing temperatures. Similarly to the graphite packed beds, it has a downward trend near the hot wall and cold wall. The local effective thermal conductivity begins to drop faster at a distance of about four pebble diameters (4 d_p) from the cold wall. Local effective thermal conductivity increases within a distance of about 3 d_p from the hot wall when compared to that at the middle positions of the bed. The near hot-wall region and the near cold-wall region are not symmetrically distributed, which may be caused by the complicated packing structure. However, the near wall region is still defined at a distance less than 4 d_p from walls in a conservative perspective. This is almost consistent to the random graphite packed beds.

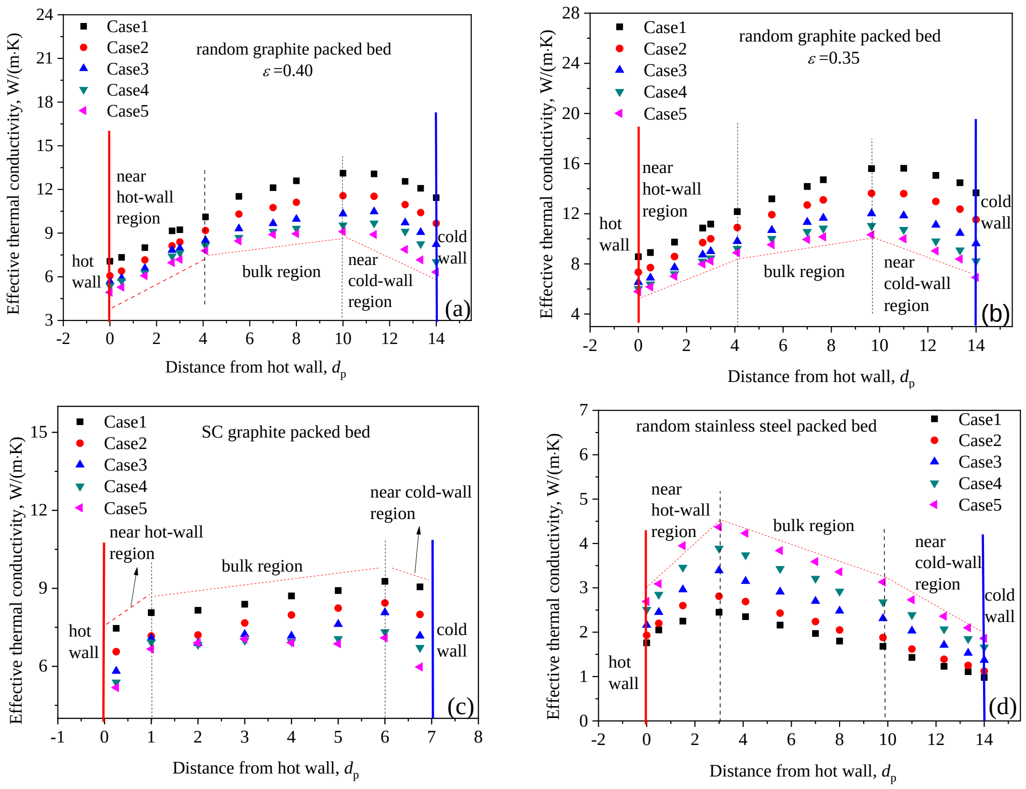

Figure 3: Effective thermal conductivity distributions in four different packed beds

3.2 Separate analysis of effective thermal conductivity in bulk regions and near wall regions

The effective thermal conductivity in the near wall regions varying with temperature is shown in Figure 4.The effective thermal conductivity in the near wall regions is scattered widely at the same temperature, especially for the random packed beds. This is because the porous structure varies sharply near walls. This indicates that the effective thermal conductivity is related to not only the temperature but the local pore characteristics (local positions). Nearly all measured values of the effective thermal conductivity in the near wall regions of all packed beds are generally smaller than those in the bulk regions at the same temperature, which is also a result of the wall effect.

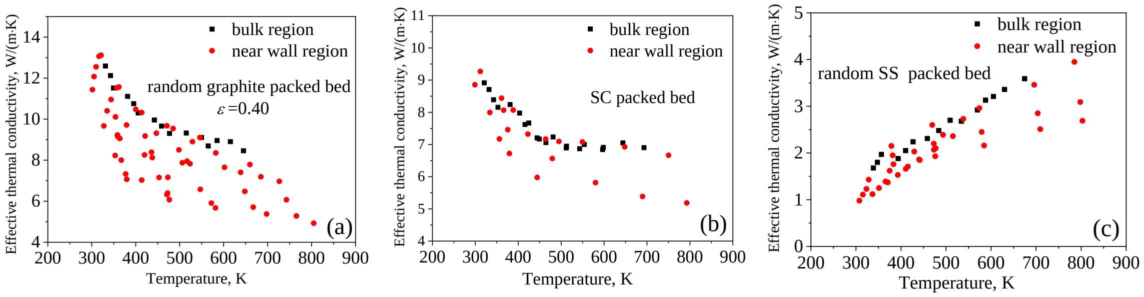

Figure 4: Effective thermal conductivity in near wall regions varying with temperature: (a) graphite packed beds (ε=0.40); (b) sc packed beds;(c) stainless steel packed beds

Total 65 measured values of the effective thermal conductivity in the bulk regions are compared with the three semi-empirical correlations considering contact conduction. Here the ZS+K correlation combines the ZS (Zehner and Schlünder,1970) correlation (neglecting contact conduction) and the Kaviany model (considering the contact conduction) (2012). Experimental values of the effective thermal conductivity in the bulk regions versus the predicted values by the ZS+K correlation are illustrated in Figure 5a. As a whole, the ZS+K correlation could describe 89.2 % of experimental values in the bulk regions within error of ±20 % and shows a 9.2 % average deviation rate and a 36.2 % maximum deviation rate. Figure 5b shows the experimental values of the effective thermal conductivity in the bulk regions versus predicted values by the ZBS correlation (Bauer and Schlünder,1978). The predicted values by the ZBS correlation agree rather well with the experimental values. About 92.3 % of the experimental values in the bulk regions are within an error of ±20 % when compared with the predicted values. The average deviation rate is 8.2 % and the maximum deviation rate is 20.7 %. All experimental values are within an error of ±30 %. As shown in Figure 5c, the Hsu correlation could describe 90.8 % of the total experimental values in the bulk regions within an error of ±20 % and shows an 11.4 % average deviation rate and a 38.9 % maximum deviation rate.

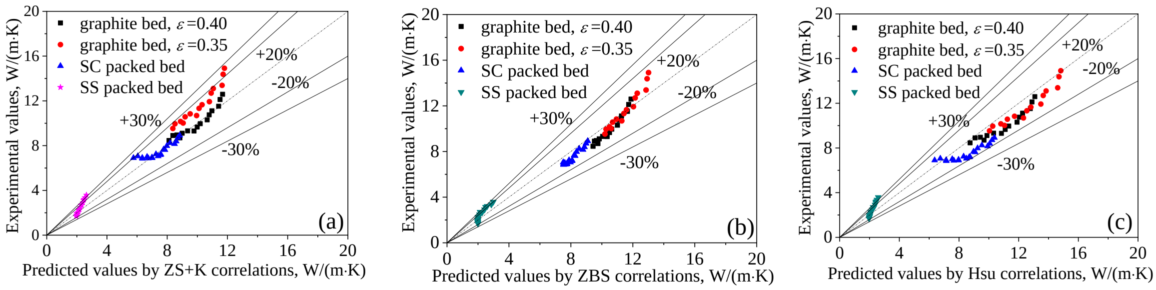

Figure 6: Experimental values in the bulk regions versus predicted values by different correlations: (a) ZS+K correlation; (b) ZBS correlation; (c) Hsu correlation

Total 165 measured values of the effective thermal conductivity in the near wall regions are compared with the three semi-empirical correlations. When compared with the predicted values by the ZS+K correlation, most experimental points (about 98.2 %) are within an error of ±40 %, as shown in Figure 6a. As a whole, the ZS+K correlations shows a 14.6 % average deviation rate and a 48.5 % maximum deviation rate. Measured values of effective thermal conductivity in the near wall regions of packed beds are compared with the ZBS correlation in Figure 6b. About 98.8 % of measured values are located within error of ±40 %. As a whole, the ZBS correlation shows a 17.4 % average deviation rate and a 41.9 % maximum deviation rate. Figure 6c shows comparisons between experimental values in near wall regions and predicted values by the Hsu correlation. The Hsu correlation could describe 93.3 % of total experimental values in the near wall regions within an error of ±40 % and shows a 20.8 % average deviation rate and a 50.3 % maximum deviation rate. Generally, the effctive thermal conductivities in the near wall regions are scattered, which poses a real challenge for the capability of the correlations.

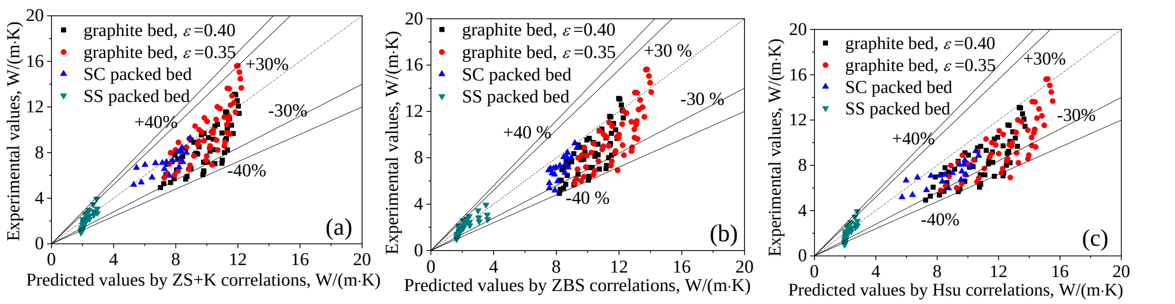

Figure 6: Experimental values in the near wall regions versus predicted values by different correlations: (a) ZS+K correlation; (b) ZBS correlation; (c) Hsu correlation

4. Conclusions

In this paper, the effective thermal conductivities in four different packed beds are experimentally studied to discuss the different behaviours in the near wall region and bulk region. It is found that the effective thermal conductivity has a downward trend as the wall is approached, which is caused by wall effect. On the basis of effective thermal conductivity distributions, the near wall region and bulk region could be determined. The near wall region can be defined within four pebble diameters from walls for random packed beds and one pebble diameter for SC packed beds, indicating wall effect in SC packed bed is weaker.

Nearly all measured values of the effective thermal conductivity in the near wall regions are generally smaller than that in the bulk regions at the same temperature. The ZBS correlation is found to give better predictions of effective thermal conductivity in the bulk region for all packed beds. In the near wall regions, the experimental results are scattered widely at the same temperature. Thus, the ZS+K correlation, the ZBS correlation and the Hsu correlation can not predict the effective thermal conductivity in the near wall regions as well as that in the bulk regions. Even the ZBS correlation describes 98.8 % of measured values in the near wall regions within error ±40 % while it describes all experimental values in the bulk regions within error of ±30 %.Generally, the ZBS correlation gives best predictions in the bulk regions and in the near wall regions with the proper empirical parameter selected. It should be noted that empirical parameters related to contact area used in the correlations significantly influence the predicted values. Further efforts should be paid to improve the prediction capability of the effective thermal conductivity correlation in the near wall regions and give a quanatitive method to determine the empirical parameters.

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