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Numerical analysis of effective thermal conductivity with thermal conduction and radiation in packed beds

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A B S T R A C T

Thermal radiation in a packed bed is controlled by temperature, emissivity, particle size, and bed structure, including void fraction, particle configuration, and the number of contact points. Thus, thermal radiation plays an important role in higher temperature operation of bed reactors. In this study, effect of the radiation/conduction ratio, namely, the Biot number with a thermal radiation coefficient, on effective thermal conductivity was investigated to clarify heat transfer in a packed bed. The Biot number for thermal radiation was defined as a function of temperature, particle size, emissivity, and configuration factor. The results obtained by the homogenization method showed that effective thermal conductivity with thermal radiation is simplified by the Biot number. Finally, the behavior of thermal radiation in the packed bed can be expressed by a sigmoidal function with the Biot number, even though the bed structure is complex.

1. Introduction

Packed beds are widely used in industry, and are expected to be used in hydrogen production [1–3]. Therefore, it is important to understand their thermal behavior. Because packed beds are often used at higher temperatures, thermal radiation cannot be neglected. Thermal expansion caused by the spatial and temporal temperature distributions during higher temperature operation cause changes in the bed structure, such as the contact area, number of contact points, and pulverization, which affect thermal radiation and conduction. These changes make modelling reactions difficult [4–6]. Accordingly, precise thermal analysis with thermal radiation is required to estimate heat and mass transfer in a bed. Effective thermal conductivity (ETC) is the most important factor, and it is a comprehensive index that includes thermal conduction and radiation [7,8]. Thermal radiation has been investigated numerically with the Biot number (Nusselt number), which is defined as the radiation/conduction ratio [9,10]. Previously, we proposed a numerical analysis with thermal convection and thermal radiation with multi-scale analysis, which can represent the microstructural change of a heterogeneous medium, such as a packed bed [11,12]. The availability of the method was confirmed quantitatively by comparison with the conventional model. However, the development of a simpler numerical technique with many parameters, such as temperature, particle size, emissivity, and configuration, for thermal radiation is still a challenge because it is difficult to apply many unit cells to the whole bed reactor. In this study, ETC for packed beds with different void fractions and particle configurations is calculated and evaluated by the Biot number, which underpins the mechanism of thermal radiation.

2. Numerical method

The homogenization method [13,14] was used to determine the ETC because it can represent microstructures by the finite element method. The Biot number is defined by the thermal conductivity of the solid, and the characteristic length and heat transfer coefficient of the thermal radiation, which is a function of the temperature, emissivity, and configuration factor between two faces of the finite elements of solids. The numerical principle of the homogenization method and the calculation technique for the Biot number have been described previously [12]. The reliability of the ETC values has been confirmed experimentally [11] and analytically [12]. Body centered cubic (BCC) and simple packed (SP) particle configurations are used in the packed bed (Fig. 1) because face centered cubic (FCC) gives similar trends. The void fraction of the packed bed, ρ, for SP and BCC, is fixed at 0.48 and 0.32 for perfect sphere packing. Contact points, n, and contact conditions are considered as the bed structure changes. For example, for BCC, $n = 0$ and $n = 8$

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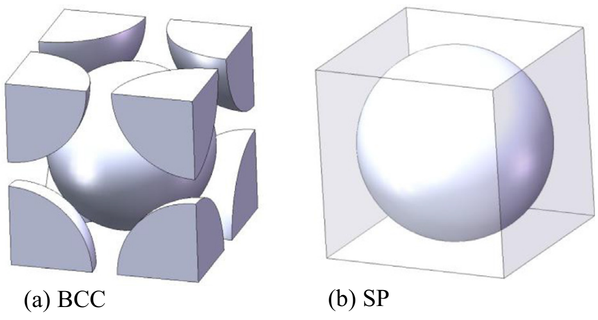
(a) BCC (b) SP

Fig. 1. Unit cells of the packed bed.

indicate non-contact and perfect contact conditions, respectively. Contact area ratio, *r*, between two particles is changed from 0.00008 to 0.008 for a unit cell face [11]. Moreover, the ranges of temperature, *T*, and emissivity, ε, are 0–1500 °C and 0.1–0.9, respectively. The thermal conductivity of the solid, λ_s, is 10 W/mK. Nitrogen is used as a gas and the gas conductivity, λ_g, is calculated [11]. Particle sizes, *d*, are varied from 0.1 to 0.00001 m owing to the size dependency of thermal radiation [12]. ETCs are calculated for these parameters and plotted as a function of the Biot number [12]. Thermal convection [11] is not considered, so as to focus on thermal radiation.

3. Results and discussion

Fig. 2 shows ETC as a function of temperature for different particle sizes for non-contact conditions (BCC, $n = 0$, and $\varepsilon = 0.5$). ETC of the packed bed composed of larger particles increases with the temperature. When the particle size is smaller than 0.001 m, ETC is almost constant. The temperature dependency of the thermal radiation must be considered for beds containing larger particles, whereas thermal radiation can be neglected for particle sizes smaller than 0.0001 m [13].

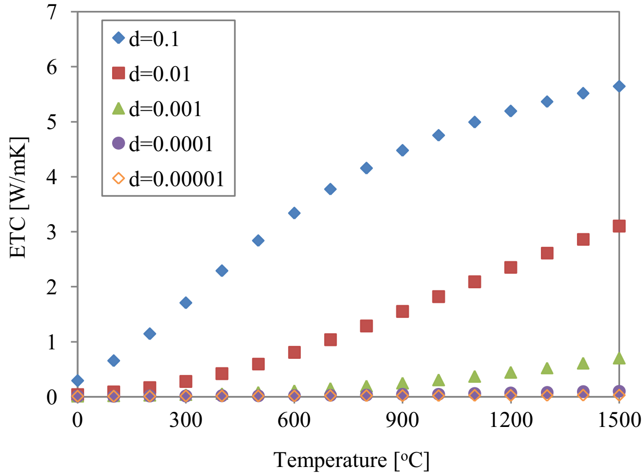

Fig. 2. ETC as a function of temperature for different particle sizes (BCC, $\varepsilon = 0.5$, $n = 0$).

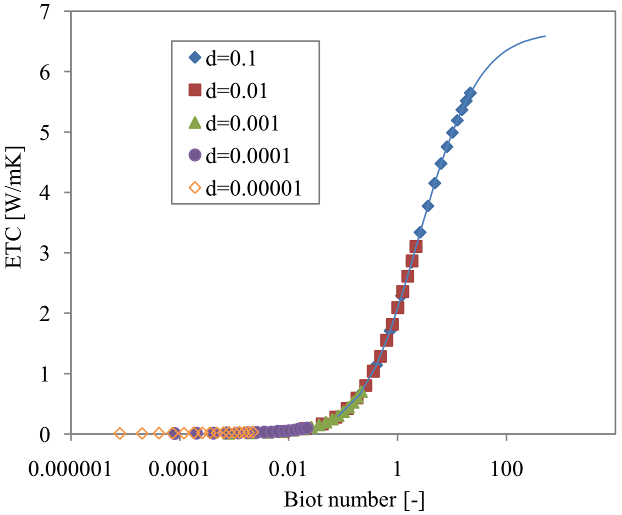

Fig. 3. ETC as a function of Biot number for different particle sizes (BCC, $\varepsilon = 0.5$, $n = 0$).

The ETC profiles for temperature shown in Fig. 2 are converted to functions of the Biot number, which is calculated by the configuration factor between two faces of the finite elements, the temperature, and the emissivity [12]. Fig. 3 shows the relation between the Biot number and the ETC. The 16 plots correspond to data at intervals of 100 °C from 0 to 1500 °C in Fig. 2. The ETC for larger particle sizes shows strong temperature dependency (Fig. 2). The ETC for smaller particle sizes (0.00001 m) show temperature independence at lower Biot numbers and are almost flat (Fig. 3). In contrast, the ETC for larger particles gradually increases with Biot number. ETC profiles are obtained from combining the data for different particle sizes as a function of Biot number to create a development curve. The trend in the plot is similar to that from data obtained with a different method [9,10]. The line shows the data for temperatures above 1500 °C and less than 0 °C; although these temperatures are not realistic for a bed reactor, the ETC is calculated for reference. The line is a single sigmoidal curve, and the line for Biot numbers outside the temperature range is flat. The ETCs for larger particles reach a maximum at a higher temperature, which is consistent with thermal convection [11].

The ETC is calculated for different emissivities (BCC, $d = 0.1$, $n = 0$). Fig. 4 shows ETC as a function of Biot number for different emissivities. A single sigmoidal curve is obtained, similar to that in Fig. 3, although plots include data for different emissivities and temperatures (0–1500 °C). Moreover, no size dependency is observed, consistent with the independence of the emissivity observed with a different analytical method [9,10]. Accordingly, the thermal radiation of the packed bed can be simplified as a rela-

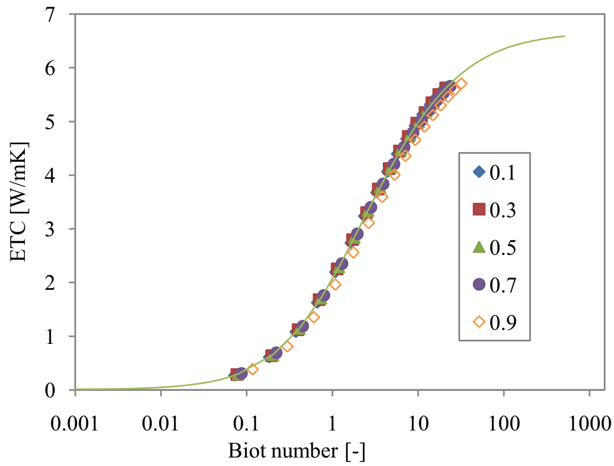

Fig. 4. ETC as a function of Biot number for different emissivities (BCC, $d = 0.1$, $n = 0$).