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Numerical analysis model for thermal conductivities of packed beds with high solid-to-gas conductivity ratio

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Abstract

A new numerical analysis model is proposed for the effective thermal conductivity of a packed bed of solid particles in static gas. The thermal conductivity of bulk region is calculated by multiplying thermal conductivity of a conventional cubic unit cell model and an effective contact number estimated to be 2.06 for a randomly distributed packed bed. Near the wall, thermal conductivity is analyzed with a model containing a container wall that has the effect of decreasing it. The calculated ratio of thermal conductivity between near wall and bulk is compared with those from literature and the physical meaning of the ratio is studied.

1. Introduction

Many studies have been conducted on measurement and prediction of thermal conductivity of packed beds filled with stationary fluid in connection with catalytic reactors, powdered nuclear fuels and so on. Recently the studies of the field receive more concerns because packed bed is adopted in the design of nuclear fusion reactor [1]. One of the most important issues in the design analysis is that the thermal conductivity of the packed bed is changed according to compressive stress, which is produced through thermal expansion of pebbles during operation. When thermal conductivity of packed bed is changed by compressive stress, in turn it effects the stress distribution by changing the temperature distribution. Therefore, the thermal analysis and the stress analysis have to be conducted simultaneously [2]. In order to study the mechanics of the heat transfer under compressive stress, it is necessary to establish a method for detailed numerical thermal analysis of packed bed.

Heat transfer of packed bed is characterized by two parameters: effective thermal conductivity of bulk region and heat transfer coefficient between container wall and packed bed. The latter is introduced since thermal conductivity is lower near wall than in bulk region. Many efforts have been made to derive analytical correlation [3–5], which would make it possible to calculate effective thermal conductivity and heat transfer coefficient using such parameters as thermal conductivity of pebbles and fluid substance, porosity and pebble diameter. However, only a few studies have been conducted on numerical analysis of effective thermal conductivity of packed bed and there are few numerical analysis models for heat transfer coefficient. Deissler et al. [6], who conducted the numerical analysis in 1958, analyzed thermal conductivity of a packed bed with the same cubic unit cell model as used to derive analytic correlation. Concerning the model, they stated: "This method, of course, still does not account for the irregular arrangement and shape of the particles. It might be possible to obtain results by using the heat conduction equation in conjunction with statistical methods, but such an analysis has not been carried out." However, the thermal conductivity calculated with their model agreed satisfactorily with the measured ones. As a result they investigated these important issues no further, stating: "It may be that for a very large number of particles, individual differences from particle to particle tend to cancel." Subsequently, the same cubic unit cell obtained reasonable results [7–9].

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Nomenclature

C	constant number in Eq. (8)
D_p	diameter of a pebble
F_w	K_{nw}/K_{ucb}
G	constant number in Eqs. (9) and (10)
H_w	heat transfer coefficient between wall and packed bed
K	thermal conductivity
K_{bed}	effective thermal conductivity of packed bed
K_{nw}	near wall thermal conductivity
K_{ucb}	effective thermal conductivity of a conventional cubic unit cell
L_{ch}	height of cell
L_{cw}	width of cell
N_{ec}	effective number of contact points
Q	total rate of heat flow
Q_{ref}	total rate of heat flow of reference unit cell
R	radius of a pebble
T	temperature
T_b	temperature of center of a pebble in contact with container wall
T_{wi}	temperature of wall inner surface
T_{wo}	temperature of wall outer surface
Greek symbols	
ϕ	azimuthal angle
θ	elevation angle

The author thinks the conventional numerical analysis models might be subject to the following problems:

- The conventional cubic unit cell models for effective thermal conductivity do not take into account irregular arrangement, which may increase the thermal conductivity through increase of contact number of particles.
- There is no numerical analysis model for heat transfer coefficient.

The purpose of this paper is to develop a new analysis model for effective thermal conductivity and heat transfer coefficient of packed bed.

The study in this paper is restricted to the packed bed consisting of metal or ceramic pebbles in stagnant gas, the characteristic of which is that the thermal conductivity of pebble material is substantially greater than that of fluid. The present approach based on physical considerations may be somewhat heuristic. On the other hand, mathematically rigorous approaches are studied in order to predict effective thermal conductivity of more extensive two-phase random media composed of particles randomly distributed throughout another material [10]. The approaches used there are interesting, but at present cannot take into account contact area and the Smoluchowski effect, both of which are important for packed bed of spheres in gas.

2. Existing analysis models

If pebbles are arranged in cubic form in the direction of heat flow, then the unit cell shown in Fig. 1(a) may be selected. The average thermal conductivity of the unit cell (K_{bed}) is calculated by Eq. (1) using the total rate of heat flow (Q), which is analyzed with the R–Z analysis model shown in Fig. 1(b). Cell width (L_{cw}) is generally fixed so as to keep the packing fraction of packed bed. Upper and lower boundary conditions for temperature (T_2 and T_1) may be an arbitrary set

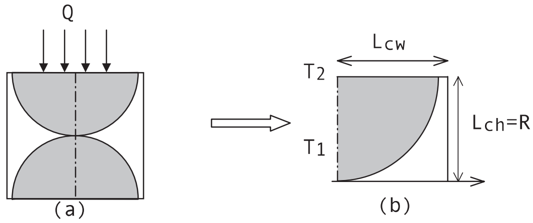

Fig. 1. Conventional cubic unit cell model for numerical analysis of effective thermal conductivity of packed bed [6].

$$Q = -\pi L_{cw}^2 K_{bed} \frac{T_2 - T_1}{R}. \quad (1)$$

Concerning heat transfer coefficient, the model used to derive the analytic correlation by Yagi and Kunii [11] is explained here, since there is no numerical analysis model for it. A unit cell is selected from wall surface to center of pebbles in contact with wall surface as shown in Fig. 2(a) since increase of porosity measured in the

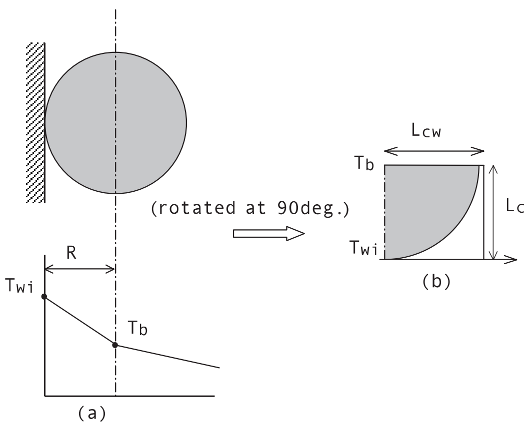

Fig. 2. Analysis model for analytic correlation of near wall thermal conductivity [11].

region is attributed to the decrease of thermal conductivity [11]. Total rate of heat flow of Fig. 2(b) is analytically calculated with the unit cell, and near wall thermal conductivity (K_{nw}) is obtained by Eq. (2). T_b and T_{wi} are temperature of center of the pebble and temperature of inner surface of the wall, respectively.

$$Q = -\pi L_{cw}^2 K_{nw} \frac{T_b - T_{wi}}{R}. \quad (2)$$

Heat transfer coefficient (H_w), conventionally determined experimentally, is calculated with the K_{nw} and K_{bed} by Eq. (3). The K_{bed} has to be obtained by some other method: an analytic correlation or measurement

$$\frac{1}{H_w R} = \frac{1}{K_{nw}} - \frac{1}{K_{bed}}. \quad (3)$$

Now, it is easily found that the analysis model of K_{nw} (Fig. 2(b)) is identical to that of K_{bed} (Fig. 1(b)). This leads to great difficulty for numerical analysis, but not for analytic correlation because any analytic correlation utilizes some mathematical and empirical approximation and correction to make calculated values accord with experimental results [3–5,11]. In the case of numerical analysis, calculated results cannot be corrected easily, therefore K_{bed} and K_{nw} coincide basically. Since the values calculated with the cubic unit cell model generally agree with experimental results for K_{bed} but not with those for K_{nw}, the cubic unit cell has been used only for the former. This suggests the importance of investigating why K_{nw} declines more than K_{bed}.

3. New analysis model

For simplicity, packed bed of cylinders is first studied respecting basic characteristics of heat transfer. An investigation is also conducted into the effect of container wall on the decrease of K_{nw}. Finally, a numerical analysis model for thermal conductivity of randomly packed bed is described.

3.1. Thermal conductivity of packed bed of cylinders

A region of packed bed consisting of cylinders is classified into two types of unit cells as shown in Fig. 3(a). One is a unit cell related to K_{nw} (Fig. 3(b)) and the other is for K_{bed} (Fig. 3(c)). Using these unit cells, numerical thermal analyses were conducted on two types of packed beds composed of aluminum cylinders and aluminum ceramics cylinders with a code of finite element method (ABAQUS). The radius is 1 mm for both cylinders, and T_1 and T_2 are 10°C and 0°C, respectively. The analyzed total rate of heat flow is shown in Table 1 as well as thermal conductivity calculated by the following equation:

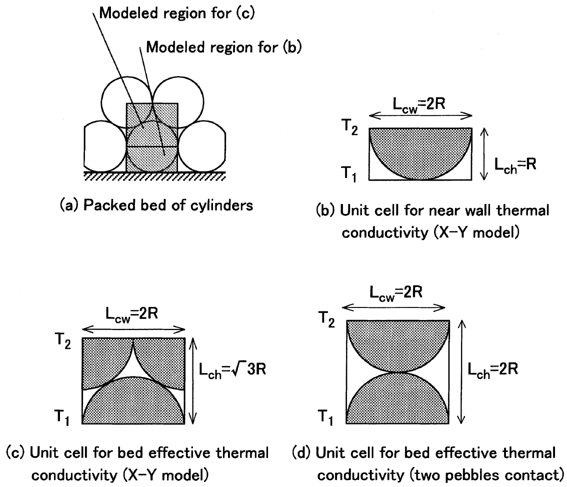

Fig. 3. Analysis models for thermal conductivity of packed bed of cylinders.

$$Q = -L_{cw} K \frac{T_2 - T_1}{L_{ch}}. \quad (4)$$

Table 1 shows that thermal conductivities near wall are less than those in bulk region in the cases of both Al cylinder bed and Al_2O_3 cylinder bed. This is exactly the result desired. Investigation of the cause gives two important characteristics of K_{bed} with high solid-to-gas conductivity ratio. One is that total rate of heat flow increases in proportion to the number of contact points. This is explained by the fact that most of the heat passes through near contact points in the pebble bed. The other is that decrease of the thermal conductivity near wall is caused by reduction of number of contact points. Although, until now, the decrease of thermal con-

Table 1
Analyzed total rate of heat flow and thermal conductivity of packed bed of cylinders[a]

Material	R (mm)	Type of unit cell	Total rate of heat flow (W)	Conductivity (W/m K)	K_{nw}/K_{bed}
Al	1	Near wall	1300	65	
Al	1	Bed	1250	108	0.60
Al_2O_3	1	Near wall	236	12	
Al_2O_3	1	Bed	210	18	0.67

[a] (Gas: He/0.1 MPa, T_1: 10°C, T_2: 0°C) Smoluchowski effect is not taken into account.

ductivity near wall has been explained by the increase of porosity, it is noticeable that this explanation is only valid for pebble bed that has small difference in thermal conductivity between pebbles and fluid. These two features are deduced from the analyzed results as follows: we introduce a new model for two pebbles in contact with each other as shown in Fig. 3(d), thermal conductivity of which is identical with that of near wall model in Fig. 3(b). Total rate of heat flow of the model in Fig. 3(d) is half that of the model in Fig. 3(b) because the temperature difference between the boundaries is the same in both models and the distance between the boundaries of the former model is twice that of the latter one. Since total rate of heat flow of the models in Fig. 3(b) and Fig. 3(c) agrees roughly with each other as shown in Table 1, total rate of heat flow of the model with two contact points in Fig. 3(c) is twice that of the model with one contact point in Fig. 3(d). Therefore, it is concluded that total rate of heat flow increases roughly in proportion to number of contact points. It is also suggested that decrease of thermal conductivity is attributable to reduction of contact point.

3.2. *Effect of container wall on near wall thermal conductivity*

An analysis model is newly devised for K_{nw}, taking into account container wall, as shown in Fig. 4. The K_{nw} can be calculated with Eq. (2) using analyzed total rate of heat flow and average temperature on the inner surface of the container wall. In the actual analysis, the average temperature is obtained by calculating temperature drop in container wall region using the thermal conductivity of container wall and the analyzed total rate of heat flow, not by numerically averaging temperature on the wall inner surface. Fig. 5 shows the K_{nw} calculated for three cases, Al pebble/SS wall, Al pebble/Cu wall and SS pebble/SS wall, as a function of thickness of container wall. The analyzed K_{nw} clearly depends on container wall and decreases with increasing thickness of wall. The decrease rate in K_{nw} of SS pebble/SS wall is about 10% at the wall thickness of 1 mm. The decrease rates for Al pebble/SS wall and Al pebble/Cu wall are saturated above wall thickness of 0.5 mm and are about 70% and 30%, respectively. These decreases of thermal conductivity result from the fact that the temperature on the wall inner surface is not distributed uniformly. For example, Fig. 6 shows that temperature near contacted point, where most of heat flows, is nearer to that of pebble center (T_b) than is average temperature on the wall inner surface, 8.98°C. Therefore, the actual total rate of heat flow is less than that with a uniform distribution of the average temperature. The uniformity of temperature on the wall inner surface decreases with

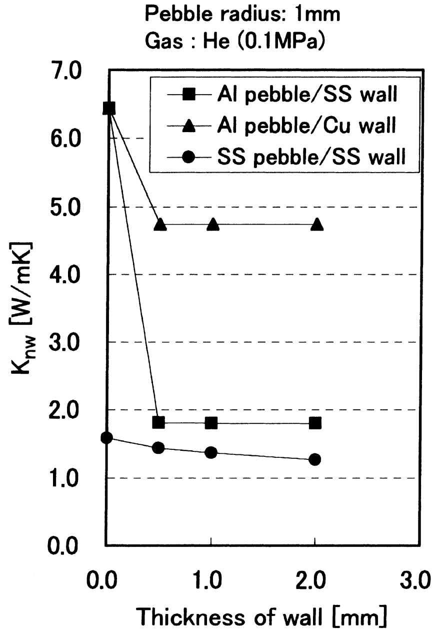

Fig. 5. Correlation between near wall thermal conductivity and wall thickness (numerically analyzed).

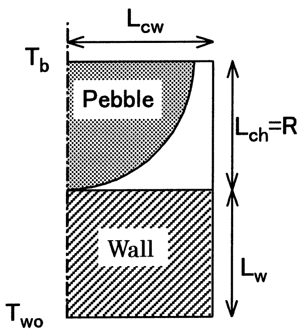

Fig. 4. A new unit cell for thermal conductivity of near wall.

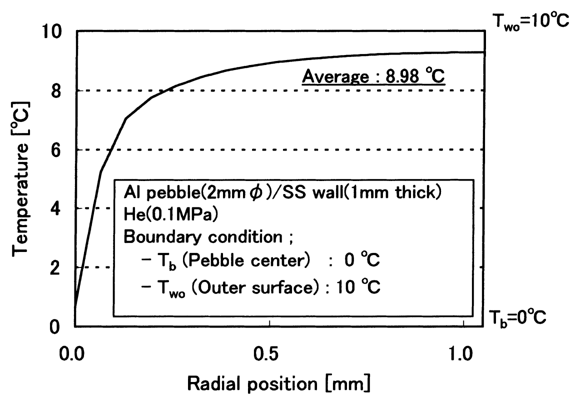

Fig. 6. The temperature distribution on the wall inner surface (Al pebble/SS wall).

an increase in thermal conductivity of pebble material and with a decrease in thermal conductivity of gas and material of container wall.

As the Smoluchowski effect is neglected in the analysis, the analyzed K_{nw} is estimated to be rather higher than experimental results. Nevertheless, it does not influence the comparison of relative magnitude described above.

3.3. New analysis model

The analysis model for K_{nw} of packed bed consisting of spherical pebbles is the same as that is described in Section 3.2. On the other hand, in order to obtain an analysis model for K_{bed}, it is necessary to extend analyses model for cylinders, presented in Section 3.1, to a 3D analysis model. Since 3D analysis is troublesome, K_{bed} is calculated here by multiplying thermal conductivity analyzed with a conventional cubic unit cell model and an effective contact number. The effective contact number is defined as the ratio of total rate of heat flow of a 3D model to the conventional cubic unit cell model and is calculated assuming that the rate of heat flow is proportional to the number of contact points.

At first, K_{nw} and K_{bed} are calculated for pebble bed packed in the close-packed structure. Unit cells of K_{nw} and K_{bed}, shown in Figs. 7(b) and (c), are selected from the dotted region in Fig. 7(a). K_{nw} is calculated as described in Section 3.2; total rate of heat flow (Q) and average temperature of inner wall surface (T_{wi}) is calculated by numerically analyzing the unit cell model in Fig. 4. The cell width (L_{cw}) is set to be radius of pebble multiplied by 1.05 to hold horizontal cross-section of the unit cell. K_{nw} is obtained by the following equation

$$Q = -\pi L_{cw}^2 K_{nw} \frac{T_b - T_{wi}}{R}. \tag{5}$$

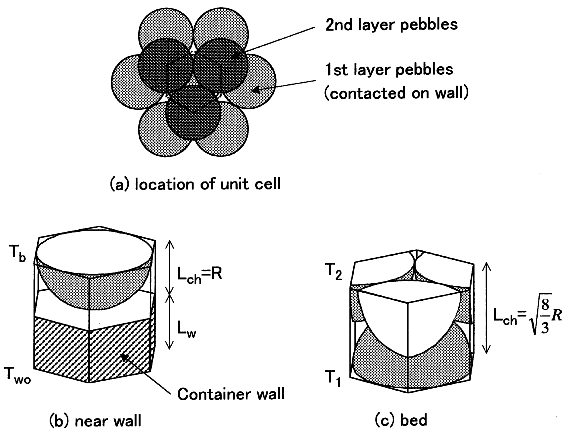

Fig. 7. Unit cell for thermal conductivity analysis of pebble bed packed in the close-packed structure.

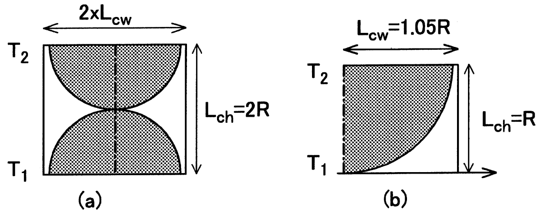

Fig. 8. Analysis model for effective thermal conductivity (R–Z model).

For calculating K_{bed}, total rate of heat flow of the model in Fig. 7(c) is required. The total rate of heat flow is assumed to be three times that of the total rate of heat flow of the model with one contact point in Fig. 8(a). In actual analysis, the conventional cubic unit cell model in Fig. 8(b) should be used, the total rate of heat flow of which is twice of that of the model in Fig. 8(a). Therefore, total rate of heat flow of the model in Fig. 7(c) is obtained by multiplying the total rate of heat flow of Fig. 8(c) by three over two. Then, K_{bed} is calculated by the equation below.

$$\frac{3}{2} Q = -\pi L_{cw}^2 K_{bed} \frac{T_2 - T_1}{\sqrt{\frac{8}{3}} R}. \tag{6}$$

Modifying the above equation, the following equation is obtained:

$$\sqrt{6} Q = -\pi L_{cw}^2 K_{bed} \frac{T_2 - T_1}{R}. \tag{7}$$

Therefore, K_{bed} of pebble bed packed in the close-packed structure is $\sqrt{6}$ ($\sim$2.45) times as large as that of the conventional cubic unit cell model.

A K_{bed} of randomly packed pebble bed can be calculated with its effective contact number. The effective contact number is calculated through two steps: (1) an effective contact number is calculated based on a pebble system consisting of a center pebble and surrounding pebbles. (2) A large number of such pebble systems are constituted by numerical simulation using random numbers. Then, effective contact numbers of those pebble systems are averaged.

Let us calculate the K_{bed} of the pebble system, where heat flows in z direction as shown in Fig. 9(a). The following assumptions are introduced:

- Temperature of surrounding pebbles (T_i) is expressed as linear function of their z position (z_i): center of the code system is set in the center pebble

$$T_i = Cz_i \quad (C \text{ is a constant number}) \tag{8}$$

- Total rate of heat flow between center pebble and surrounding pebble is proportional to difference of center temperature of the two pebbles.

Then, total rate of heat flow of income and outcome coincide each other and are obtained with a constant G by the next equation as shown Fig. 9(b)

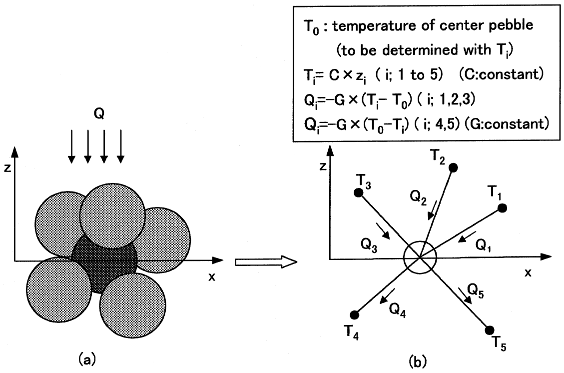

Fig. 9. Analysis model of rate of heat flow of randomly distributed packed bed comprising of a center pebble and five surrounding pebbles.

$$Q = Q_1 + Q_2 + Q_3 \\ = -G(T_1 - T_0) - G(T_2 - T_0) - G(T_3 - T_0), \qquad (9)$$

$$Q = Q_4 + Q_5 = -G(T_0 - T_4) - G(T_0 - T_5). \qquad (10)$$

T_0 is calculated by the following equation obtained through Eqs. (9) and (10):

$$T_0 = \frac{1}{5}(T_1 + T_2 + T_3 + T_4 + T_5). \qquad (11)$$

T_0 and Q are easily generalized as follows:

$$T_0 = \frac{1}{N}(T_1 + T_2 + T_3 + \cdots + T_N), \qquad (12)$$

$$Q = \sum_i [-G(T_i - T_0)] \\ = \sum_i [-GC(z_i - z_0)] \quad (\text{for } i \text{ where } T_i - T_0 > 0). \qquad (13)$$

On the other hand, rate of heat flow of reference unit cell (Fig. 8(a)) is calculated by the following equation since difference of center temperature of two pebbles is $C \times 2R$.

$$Q_{\mathrm{ref}} = G \times C \times 2R. \qquad (14)$$

Then, effective contact number (Q/Q_{ref}) is calculated if R and z positions of surrounding pebbles are specified. G and C are canceled out in the calculation of effective contact number, and so it is preferable that both parameters be set to 1.

Next, effective contact number of randomly distributed pebble bed should be calculated. Surrounding pebbles are designated by spherical coordinates with origin of a center pebble as shown in Fig. 10. Radial coordinate r of surrounding pebbles is fixed to be $2R$ because two pebbles are contacted. A pebble system is made with random numbers by the next procedures.

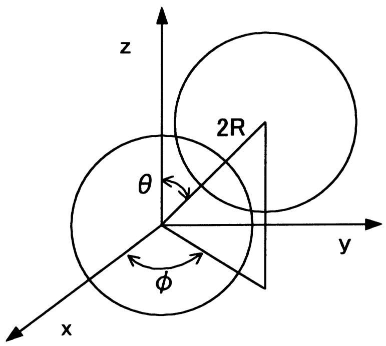

Fig. 10. Coordination system for calculation of an effective contact number.

- First surrounding pebble is constructed by randomly setting θ and ϕ.
- Second or subsequent surrounding pebbles are set in the same way, and if the added pebble interferes with the former surrounding pebbles, new position is tried to a total of 40,000 times. By increasing the tried number from 40,000 to 100,000, the contact number increased by only 0.5% in 1000 pebble systems attempted. The tried number is therefore sufficiently large for accuracy within a few percent.

Effective contact number and contact number are given in Fig. 11 for the first 100 data of 5000 pebble systems calculated. The average contact number is about 8.3, and the average effective contact number is 2.06, which is naturally less than that of the close-packed structure, 2.45. The computational errors of the averaged contact numbers and the averaged effective contact number are estimated to be less than 1% by the examination of those numbers for every 1000 pebble systems of the 5000 pebble systems calculated.

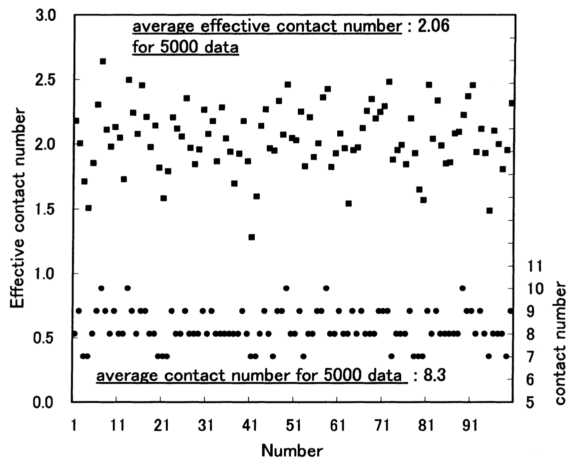

Fig. 11. Calculated effective contact number and contact number for the first 100 data of 5000 pebble systems.

In short, K_{nw} is calculated with a model taking into account container wall. K_{bed} is obtained by multiplying an effective thermal conductivity calculated with a conventional cubic unit cell and an effective contact number estimated above as 2.06 for randomly packed pebble bed. Since this effective contact number may depend on packing fraction, study is required on the correlation between an effective contact number and a packing fraction.

4. Validation of new analysis model

The present model does not take into account surface roughness of pebbles which often substantially influences K_{bed} and has not been solved fully yet. This leads to overestimation of thermal conductivity of pebble beds as described below. So, the present model is validated by comparing the analyzed ratio of K_{nw} to K_{bed} with measured ones from literature. The effect of surface roughness may be as large for contact of two pebbles as for contact between a pebble and a wall, and then that is probably eliminated by adoption of the ratio.

Before the discussion of the ratio of K_{nw} to K_{bed}, validation of the analyzed K_{nw} and K_{bed} is described. Fig. 12 provides the ratio of analyzed thermal conductivity, K_{nw} and K_{bed}, to those measured by Daldonne et al. [12]. These analyses take into account the Smoluchowski effect, which decreases thermal conductivity of gas in the microscopic region from solid surface, an order of mean free path of the gas. The gas region of the analyses is divided into several sub-regions according to the width in the direction of heat flow, and thermal conductivity of each sub-region is calculated with the equation suggested by Olander in the same way as is described in Ref. [9].

As Fig. 12 shows, the present model overestimates K_{nw} and K_{bed} of Al_2O_3 pebble bed roughly from 2 to 2.5 times. If the effective contact number, 2.06, had not been introduced in the analysis as usual, then the analyzed K_{bed} would satisfactorily agree with the measured ones, but K_{nw} is not benefited since the effective contact number is not applied to K_{nw}. On the other hand, relatively good agreement is apparently attained regarding Al pebble bed with the aid of the effective contact number. This agreement is partly explained by increase of the measured K_{nw} and K_{bed}, which occurs in the case of Al pebble bed and not in the case of Al_2O_3 pebble bed. This increase is not taken into account in the present analysis and probably caused by compressive stress produced inevitably to some extent in that kind of experimental system as follows. The experimental system is composed of two annular cylinders with an electric heater installed inside the inner cylinder and pebble bed contained between the two cylinders [12]. Thermal conductivity and heat transfer coefficient are measured from the radial temperature gradient generated in the pebble bed by the electric heater. Higher temperature in the center region makes compressive stress in the pebble bed through difference thermal expansion between pebbles and the outer cylinder. This effect is verified by another experiment [13] and the analysis of its stress distribution [2]. But the thermal conductivity of Al_2O_3 pebble bed is probably not changed by compressive stress because this effect is not observed on pebble bed of lithium zirconate, the same ceramics as Al_2O_3 [14]. In short, it is very difficult to analyze thermal conductivity of pebble bed without a sort of correction factor, such as contact area, surface roughness and so on, and if one of those correction factors is introduced, validation of an analysis model is difficult. So the ratio of K_{nw} to K_{bed} is aimed at here as described below.

In Fig. 13, the analyzed ratios of K_{nw} to K_{bed} are compared with the measured ones. This figure shows

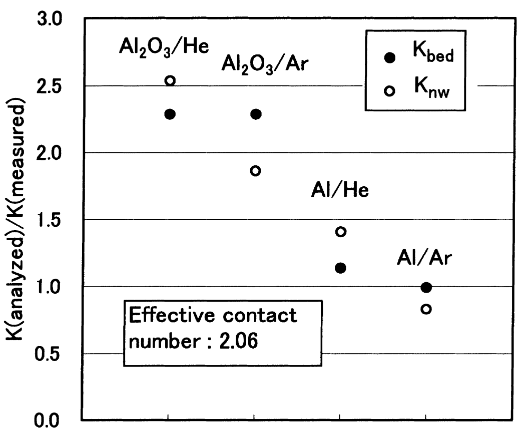

Fig. 12. Ratio of analyzed thermal conductivity to measured ones.

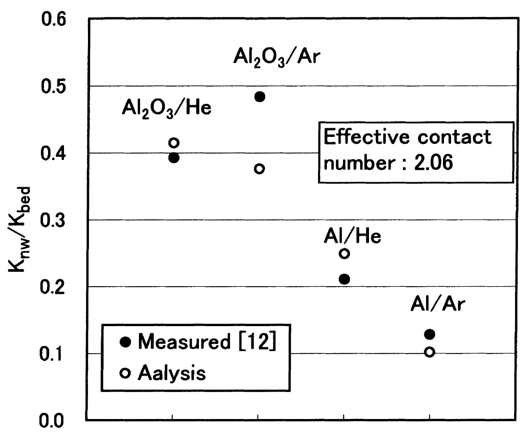

Fig. 13. Ratio of thermal conductivity of near wall and bulk of packed bed.

Table 2
Effective thermal conductivity of near wall and bulk of packed bed (measured data from literature)[a]

Bed	Diameter (mm)	K_{bed} (W/m K)	H_w (W/m^2 K)	K_{nw} (W/m K)[b]	K_{nw}/K_{bed}	Ref.
Al_2O_3/He	2	1.66	1070	0.65	0.39	[12]
Al_2O_3/Ar	2	0.38	357	0.18	0.48	
Al/He	2	6.62	1767	1.39	0.21	[12]
Al/Ar	2	3.86	565	0.49	0.13	
SS/He	2	2.57	2072	1.15	0.45	[15]
SS/Ar	2	1.31	582	0.40	0.31	
SS/He	4	2.18	1122	0.74	0.34	[15]
SS/Ar	4	0.78	190	0.15	0.20	

[a] (Gas: 0.1 MPa).
[b] Defined here as $1/(1/(H_w \times 0.5 D_p)+1/K_{bed})$.

these ratios are all under 0.5 and have two features. One is that the ratio for Al pebble bed is less than that for Al_2O_3 pebble bed. The other is that the ratio for Ar gas is less than that for He gas excluding measured data for Al_2O_3 pebble bed; the exception is discussed later. These features are explained as follows: K_{bed} is calculated by multiplying effective contact number (N_{ec}) and thermal conductivity of cubic unit cell model (K_{ucb}) as expressed by Eq. (15). Although K_{nw} is directly analyzed with a model containing container wall, here it is expressed using thermal conductivity analyzed with the same cubic unit cell model as for K_{bed}. Then, K_{nw} is obtained by multiplying K_{ucb} and a factor, F_w, which represents decrease of thermal conductivity caused by container wall and is calculated by dividing K_{nw} by K_{ucb}. Then K_{nw} is expressed by Eq. (16). The ratio of K_{nw}/K_{bed} is calculated by multiplying F_w and is inverse to N_{ec} as expressed by Eq. (17).

$$K_{bed} = N_{ec} \times K_{ucb}, \tag{15}$$

$$K_{nw} = F_w \times K_{ucb}, \tag{16}$$

$$\frac{K_{nw}}{K_{bed}} = \frac{F_w}{N_{ec}}. \tag{17}$$

Many important characteristics are obtained from Eq. (17). Since N_{ec} is about 2.0 and F_w is generally less than 1, K_{nw}/K_{bed} is generally less than 0.5. K_{nw}/K_{bed}, as well as F_w, decreases with an increase in thermal conductivity of pebble material and with a decrease in thermal conductivity of gas and material of container wall. Therefore, K_{nw}/K_{bed} for Al pebbles is less than that for Al_2O_3 pebbles and K_{nw}/K_{bed} for Ar gas is less than that for He gas. Concerning the exception noted above, two more experimental data of SS pebble support the conclusion that the K_{nw}/K_{bed} decreases as thermal conductivity of gas decreases as shown in Table 2. Perhaps the exception suggests the need for careful re-investigation of the heat transfer characteristics of the measured Al_2O_3 pebble bed.

It is concluded that the effective contact number is essential to account for near wall thermal conductivity being less than that of bulk region, and the ratio of the thermal conductivity between near wall and bulk region is an important parameter for characterizing the heat transfer of a packed bed.

An effective contact number, about 2, is newly introduced here and generally results in overestimation of effective thermal conductivity since a usual cubic unit cell model has been successful to some extent without taking into account increase of a contact number in randomly packed pebble beds. This may be canceled by properly taking into account surface roughness of pebble and wall, which have been introduced already to account for the dependency of gas pressure on effective conductivity [9].

5. Conclusions

Effective thermal conductivity of a packed bed of solid particle in static gas cannot be analyzed with a conventional cubic unit cell model. What is required is a model that takes into account increase of contact number in a randomly distributed packed bed. A new analysis model is proposed whereby the effective thermal conductivity is calculated by multiplying effective thermal conductivity of a conventional cubic unit cell model and an effective contact number, which is estimated to be 2.06 for a randomly distributed packed bed. The decrease of thermal conductivity near wall is attributed to two causes: reduction of contact number there and finite value of thermal conductivity of container wall. Thus, a new analysis model for near wall thermal conductivity is proposed which features introduction of container wall. With respect to the ratio of thermal conductivity near wall to that in bulk region, there is good agreement between the results of analysis with the proposed model and measurement results in the literature.

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