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Thermal conductivity of a beryllium gas packed bed

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Abstract

An unsintered packed bed has been suggested as a material form for the solid breeder and multiplier in fusion reactor blankets. Study of the effective bed thermal conductivity can provide tools for analysis of the blanket performance under different operating conditions, and for analysis of how to control actively the thermal behavior of the blanket. Issues of particular interest are the ability to predict and to control the thermal conductivity. The UCLA 2-D model is used to study the effects of the particle diameter, solid-to-gas conductivity ratio, bed porosity, contact area and surface roughness characteristics on the bed thermal conductivity. The study shows that all the parameters except the bed porosity play important roles in determining the bed thermal controllability. The effect of the bed porosity is minimal. Four models (the UCLA 2-D model, the modified Hall–Martin model, the SZB model, and the Kunii–Smith model) were compared with the recent UCLA single-size beryllium packed bed experimental data. The sensitivity of each model to uncertainties in the input parameters, such as the surface roughness characteristics and particle-to-particle contact area, are examined. The UCLA 2-D model gives the most reliable prediction of the Be–He packed bed effective thermal conductivity, using reasonable parameters. The modified Hall–Martin model predictions agree well with the experimental data, using a larger empirical particle-to-particle contact area. The SZB model works well for Be–N_2 or Be–air particle beds. The Kunii–Smith model is not suitable for a packed bed with a high solid-to-gas conductivity ratio.

1. Introduction

The thermal conductivity of unsintered packed beds (i.e. packed powders) is a subject that has been investigated extensively, both theoretically and experimentally, because of its many practical applications. Vibro-compacted gel spheres of $(U,Pu)O_2$ have been recommended as a type of fuel for fast reactors [1]. Sphere-pac fuels have been recommended as alternatives to cylindrical rods in light water reactors (LWRs) and liquid metal fast breeder reactors (LMFBRs). The effective thermal conductivity of the packed beds will affect the heat removal rate in the case of the reactor core meltdown or shutdown. In fusion, packed beds have been suggested [2] as a material form for the solid breeder and multiplier in the blanket.

Solid breeder and neutron multiplier materials can be manufactured as a sphere-pac or sintered block. The sintered block provides the benefits of high thermal conductivity and possible design simplicity. Issues include the effects of thermal expansion and thermal stresses, and the prediction of thermal resistance at the cladding interfaces. The sphere-pac form, which is basically a packed particle bed, is of particular interest for beryllium, where temperature control is required (such as to accommodate power variation), since the particle bed thermal conductivity could be controlled through purge gas adjustments (pressure, composition, flow

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rate, etc.). However, the effective thermal conductivity of a packed bed is lower than that of a sintered block. For solid breeders, the attractiveness of the sphere-pac form rests mainly on its potential for uniform and predictable behavior under operating conditions, as opposed to a sintered block that might crack or fragment because of high thermal stresses and whose interface conductance might vary considerably.

2. Packed bed effective thermal conductivity models

2.1. Modified model of Hall and Martin: UCLA version [3]

This model is based on that of Hall and Martin [1]. In the original Hall–Martin model, the following three assumptions were made to simplify the problem: point contact between spheres; one-dimensional heat flow; cubic and square-packed cylinder arrangements as representative of cases with high and low porosities respectively.

The modified Hall–Martin model (UCLA version) has used a finite contact area instead of point contact. This is closer to the reality and may make some contribution to offset the bias caused by the one-dimensional heat flow assumption. The effect of this modification is particularly important for cases with high ratios of solid-to-gas thermal conductivity. Cubic-packed and square-packed cylinder arrangements do not reflect the actual arrangement for single-size particle beds, and even less so for binary-size beds. According to McGeary [4], for single-size spheres, the particles tend to be packed in an orthorhombic pattern. The UCLA-modified Hall–Martin model has used the orthorhombic arrangement as the representation for the single-size packed bed.

2.2. Schlünder–Zehner–Bauer model [5–8]

In this model, the bed is simulated by a standard cell containing two contacting particles (see Fig. 1). The heat flow is divided into three parallel paths. The first path represents conduction and radiation through the gas-filled voids and has an area fraction of $1-(1-\varepsilon)^{1/2}$. The second path represents conduction through the solid and gas phases, with radiation between solid surfaces, and has an area fraction of $(1-\delta)(1-\varepsilon)^{1/2}$. Finally, the solid–solid conduction path has an area fraction of $\delta(1-\varepsilon)^{1/2}$. The effect of several factors, including the particle size distribution, shape factor, bed porosity, wall effect, etc., can be studied using this model.

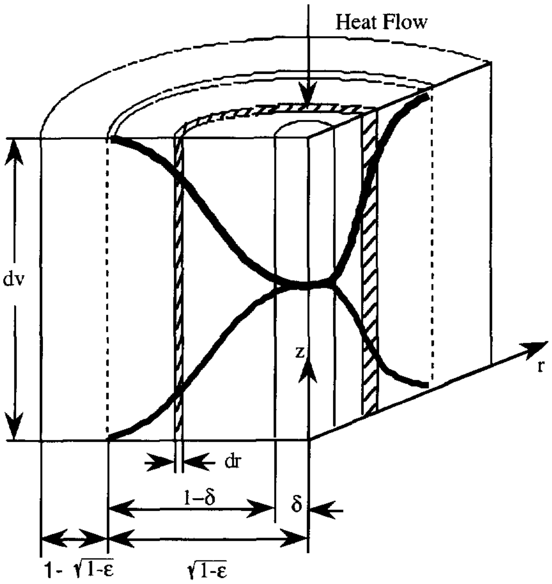

Fig. 1. Unit cell for SZB model.

2.3. UCLA two-dimensional model [9]

The two-dimensional unit cell used in this model includes part of a sphere inside an orthorhombic pack. Every sphere inside the bed can be divided into 24 of these cells, which are identical to each other because of symmetry. In this study, the author used a spherical grid instead of a cartesian grid to overcome the large temperature jump condition at the solid–gas interface. In addition to the use of the spherical grid, the surface roughness characteristics are also considered in this model. For details about this model, see ref. [9].

2.4. Model of Kunii and Smith [10]

It is presumed that the particles in this model are surrounded by stagnant fluid. Heat transfer is assumed to occur in the vertical direction, by the following mechanisms: (1) heat transfer through the fluid in the void space by conduction and by radiation between adjacent voids (when the voids are assumed to contain a non-absorbed gas); (2) heat transfer through the solid phase—(a) heat transfer through the contacct surface of the solid particles; (b) conduction through the stagnant fluid near the contact surface; (c) radiation between surfaces of the solid (when the voids are assumed to contain a non-absorbent gas); (d) conduction through the solid phase.

Overall, mechanisms 1 and 2 are in parallel with each other. In mechanism (2), part (d) is in series with the combined result of parallel part-mechanisms (a), (b) and (c).

3. Parametric analysis of beryllium bed effective thermal conductivity

It is believed that the packed bed effective thermal conductivity varies with the solid-to-gas conductivity ratio, i.e. k_s/k_g, particle size, porosity, contact area, roughness, etc. A parametric study based on the UCLA two-dimensional model was performed to gain a better understanding of the beryllium particle bed thermal behavior.

A single-size beryllium bed (particle diameter, 1 mm; roughness height, 1 μm; $r_1/r_2 = 0.2$; porosity, 0.39; contact area parameter $(r_c/r_p)^2 = 5 \times 10^{-5}$) with helium as the cover gas was used as the reference case. The effects of the particle diameter, roughness, r_1/r_2, cover gas, porosity and contact area on the ratio of the effective thermal conductivity (k_{eff}) of the packed bed at 2 atm to that at 0.2 atm, which is a measure of the bed thermal controllability, is studied. The ratio $k_{eff}(2\ \text{atm})/k_{eff}(0.2\ \text{atm})$ is considered to be a practical range for the controllability of the effective thermal conductivity of a beryllium packed bed with a low pressure gas purge.

As the particle size is increased from 0.025 to 2 mm, the controllability factor is reduced from 2.2 to 1.3; maximum controllability can be obtained when k_s/k_g is in the range 200–1000. At a temperature of 400 °C, the ratio of the thermal conductivity of beryllium to that of helium is about 422, and the ratio of the thermal conductivity of aluminum to that of helium is about 635. Therefore, at temperature of 400 °C, both Be–He and Al–He packed beds can achieve the best controllability. The effect of the porosity on the controllability is minimal; better thermal controllability can be achieved for low contact areas; the roughness of the sphere is modelled as the small cyclinder regularly distributed on the sphere surface, with $(r_1/r_2)^2$ representing the fraction of the particle surface area covered by the roughness. For a roughness height less than 0.3 μm, the smaller the area covered by roughness is, the better will be the thermal controllability. For a roughness height larger than 1 μm, the larger the area covered by roughness is, the better will be the achievable thermal controllability. For details about the parametric study, see ref. [11].

4. Comparison of the models with experimental data

The available models and correlations for predicting the packed bed effective thermal conductivity were described in Section 2. As a result of the lack of sufficient experimental data on the beryllium particle bed effective thermal conductivity, most of these models have not been benchmarked. In this section, four effective thermal conductivity models are compared with the recent UCLA beryllium particle bed experimental data [12,13]. The senstivity of each mode to various effects, such as the surface roughness, particle-to-particle contact area, etc., as well as uncertainties in input parameters are examined. The models can be summarized as follows, with the operating conditions of each test run listed in Table 1.

The UCLA two-dimensional model involves solving

$$\frac{\partial}{\partial r}\left(r^2 k \frac{\partial T}{\partial r}\right) + \frac{1}{\sin\Phi}\frac{\partial}{\partial\Phi}\left(k \sin\Phi \frac{\partial T}{\partial\Phi}\right) = 0$$

with

$$\frac{\partial T}{\partial\Phi} = 0 \qquad \phi = 0$$

$$T = T_1 \qquad \phi = \pi/2$$

$$T = T_2 \qquad \phi \leqslant \phi_1,\ r\cos\Phi = r_b$$

$$\frac{\partial T}{\partial x} = 0 \qquad \phi > \phi_1,\ r\sin\Phi = r_f$$

Table 1
Operating conditions of each test run [12]

Test	Cover gas	Bed temperature (°C)	Packing factor	Packing technique
1	Helium	30–40	0.60	Poured in
2	Helium	30–40	0.60	Poured in
3	Helium	30–40	0.60	Poured in
4	Nitrogen	30–40	0.60	Poured in

The modified Hall–Martin model (UCLA version) can be stated as

$$k_{\mathrm{eff}} = \frac{k_{\mathrm{s}}(\pi r_{\mathrm{c}}^2/r_{\mathrm{b}}) + \displaystyle\int_{\phi_{\mathrm{c}}}^{\pi/2} \frac{k_{\mathrm{g}} 2\pi r_{\mathrm{p}}^2 \sin\phi \cos\phi \,\mathrm{d}\phi}{(k_{\mathrm{g}}/k_{\mathrm{s}} - 1) r_{\mathrm{p}} \cos\phi + r_{\mathrm{b}} + g/2}}{(r_{\mathrm{p}}^2/r_{\mathrm{b}})\{4\sin(\pi/3) f_{\mathrm{cor}} + \pi(1 - f_{\mathrm{cor}})\}}$$

with $r_{\mathrm{b}} = r_{\mathrm{b}} \cos\phi_{\mathrm{c}}$.

The SZB mode is given by

$$\frac{k_{\mathrm{eff}}}{k_{\mathrm{g}}} = \{1 - (1-\varepsilon)^{1/2}\}\frac{k_{\mathrm{H}}}{k_{\mathrm{g}}} + (1-\varepsilon)^{1/2}\left\{(1-\varepsilon)k_{\mathrm{e}} + \frac{\delta k_{\mathrm{s}}}{k_{\mathrm{g}}}\right\}$$

The Kunii–Smith model is given by

$$\frac{k^0_{\mathrm{eff}}}{k_{\mathrm{g}}} = \varepsilon\left(1 + \beta\frac{h_{\mathrm{rv}} D_{\mathrm{p}}}{k_{\mathrm{g}}}\right) + \frac{\beta(1-\varepsilon)}{1/\{1/\Phi + (D_{\mathrm{p}}/k_{\mathrm{g}})(h_{\mathrm{p}} + h_{\mathrm{rs}})\} + \gamma(k_{\mathrm{g}}/k_{\mathrm{s}})}$$

4.1. Comparison of the modified Hall–Martin model (UCLA version) with test results

Comparisons of the modified Hall–Martin model (UCLA version) with UCLA test results [12,13] are shown in Fig. 2. In the model prediction (solid line), point contact is assumed, since no external load is applied to the particle bed. The elastic contact radius resulting from the weight of particles is minimal, and $(r_{\mathrm{c}}/r_{\mathrm{p}})^2$ is believed to be of the order of magnitude of 10^{-5} or smaller. It is obvious that the predicted values are much lower than the experimental results, particularly for the Be–N_2 packed bed, since it has a higher ratio of $k_{\mathrm{s}}/k_{\mathrm{g}}$. This observation is consistent with the discussion in ref. [3]. An unrealistically high contact area can be imposed to reduce the test data (broken line in Fig. 2). A value of $r_{\mathrm{c}}/r_{\mathrm{p}} = 0.037$ seems adequate to reproduce tests 1–4.

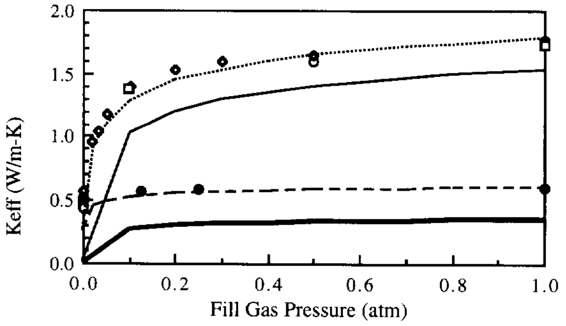

Fig. 2. Comparison of the modified Hall–Martin model with tests 1–4: ○, test 1; ◆, test 2; □, test 3; ——, point contact for Be–He; ····, $r_{\mathrm{c}}/r_{\mathrm{s}} = 0.037$ for Be–N_2; ○, test 4; ——, point contact for Be–N_2; – – –, $r_{\mathrm{c}}/r_{\mathrm{s}} = 0.037$ for Be–N_2.

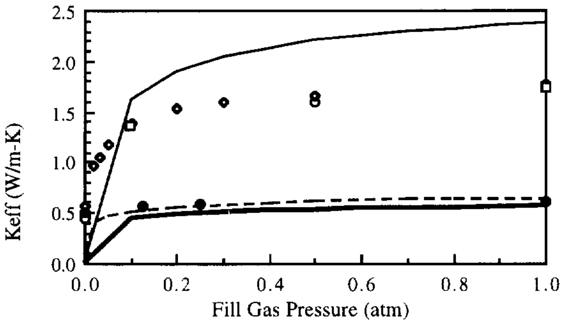

Fig. 3. Comparison of the SZB model with tests 1–4: ○, test 1; ◆, test 2; □, test 3; ——, model prediction of Be–He; ●, test 4; ——, point contact for Be–N_2; – – –, $(r_{\mathrm{c}}/r_{\mathrm{s}})^2 = 2 \times 10^{-5}$ for Be–N_2.

The modified Hall–Martin model is a 1–D heat flow model. The regular packing array used by this model tends to overpredict the bed thermal conductivity, while the 1–D heat flow assumption tends to underpredict the bed thermal conductivity. The use of a finite contact area instead of the previous point contact assumption means that the model can reproduce the experimental data by changing the contact area. At present, however, reliable experimental data are needed to benchmark the model (such as obtaining the empirical contact area), before the model is actually used for any prediction.

4.2. Comparison of the SZB model with UCLA test results

Fig. 3 shows a comparison of the SZB model with the UCLA test results. Again, point contact is assumed in the model evaluation. It is interesting that the SZB model tends to overestimate the bed effective thermal conductivity of the Be–He particle bed and to underestimate the bed effective thermal conductivity of the Be–N_2 particle bed. Nothing can be done to improve the model evaluation for the Be–He particle bed. A value of 2×10^{-5} for $(r_{\mathrm{c}}/r_{\mathrm{p}})^2$ can reproduce quite closely the result of test 4. Therefore, the SZB model seems to be more suitable for very high solid-to-gas thermal conductivity beds.

The effect of radiant heat transfer on the bed thermal conductivity is studied using this model. When the emission ratio of the solid surface is changed from 10^{-5} to 1.0, the bed thermal conductivities of the Be–N_2 and Be–He beds are increased by 2.4% and 0.7% respectively. Since the experimental data have an uncertainty of ± 10%, the contribution to the bed thermal conductivity resulting from the radiant heat transfer is actually negligible for the test case (it depends on the temperature).

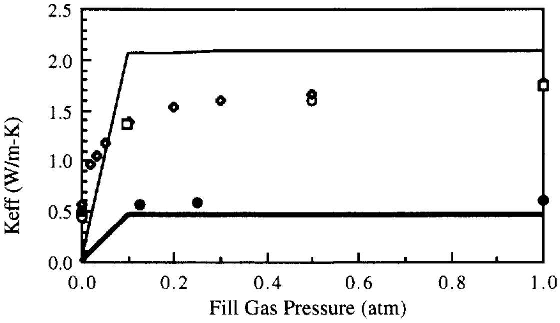

Fig. 4. Comparison of the model of Kunii and Smith with tests 1–4: ○, test 1; ◆, test 2; □, test 3; ——, model prediction for Be–He; ●, test 4; ——, model prediction for Be–N_2.

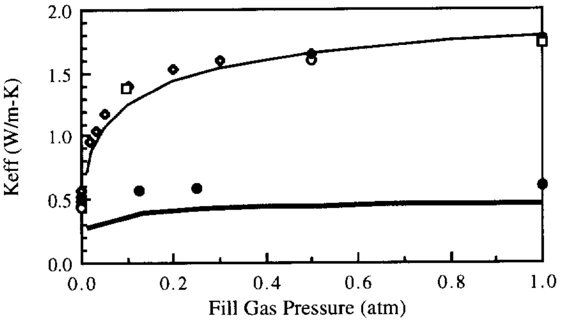

Fig. 5. Comparison of the UCLA two-dimensional model with tests 1–4: ○, test 1; ◆, test 2; □, test 3; ——, model prediction for Be–He; ●, test 4: ——, model prediction for Be–N_2.

Similarly to the modified Hall–Martin model, the SZB model is also a one-dimensional model with a regular array and finite contact area. Hence, this model is similar to the modified Hall–Martin model. However, it is not suitable for packed beds with low solid-to-gas thermal conductivity ratios.

4.3. *Comparison of the Kunii–Smith model with UCLA test results*

As for the SZB model, the Kunii–Smith model overestimates the bed effective thermal conductivity of Be–He particle beds and underestimates the bed effective thermal conductivity of Be–N_2 particle beds (see Fig. 4). Unlike the previous two models, however, the bed thermal conductivity is related to the number of particle contact points, and the number of particle contact points is a function of the bed porosity. Therefore, for a packed bed with a given porosity, the bed thermal conductivity is a fixed value. Therefore, it does not seem that it can be applied to a particle bed with a high ratio of k_s/k_g, such as a Be–He or Be–N_2 bed.

4.4. *Comparison of the UCLA two-dimensional model with UCLA test results*

A comparison of the UCLA 2-D model prediction results with the UCLA test data is shown in Fig. 5. Unlike the previous models discussed above, the surface roughness is accounted for in this model. To model the surface roughness, many electron microscopic graphics should be taken, and statistical analysis should be made to determine the mean surface roughness height and the fraction area covered by the roughness. This is very expensive and time-consuming work, and it is out of the scope of this paper. However, a few electron microscopic graphics were taken to estimate the surface roughness characteristics [13]. An approximate estimate of the value of the roughness height is believed to be in the neighborhood of 1–2 μm, and the fraction of the surface area covered by the roughness seems to be less than 1%, which means that the ratio r_1/r_2 is below the value of 0.1.

It is expected that the predicted results for test 4 (Be–He particle bed, taken by Tillack et al.) will not agree well with the experimental data. This may be caused by the inaccurate estimation of r_1/r_2 and the roughness height δ.

Since this is a 2-D model and includes so many parameters, we can study each parameter's effect and find the parameter which has the largest impact on the bed thermal conductivity. The use of 2-D heat flow instead of 1-D flow means that we can use a reasonable contact area to predict the bed thermal conductivity.

5. Concluding remarks

In the research work reported here, four bed effective thermal conductivity models (the UCLA two-dimensional model, the modified Hall–Martin model (UCLA version), the SZB model and the Kunii–Smith model) were described. Parametric analysis was performed to gain a better understanding of the thermal behavior of the beryllium gas particle bed and to investigate how to control actively the solid blanket temperature profile (through control of the bed effective thermal conductivity). The effects of various parameters on the particle bed thermal controllability were studied, and the UCLA two-dimensional model was used for the analysis. The result was presented in terms of the change in the bed thermal controllability, which is defined as the ratio of the k_{eff} value at 2 atm to k_{eff} at 0.2 atm. The following conclusions were reached.

(1) The thermal controllability decreases with the particle size.

(2) The thermal controllability increases with the solid-to-gas conductivity ratio, reaches a maximum value of 1.46 at $k_s/k_g \approx 500$ and then decreases to a value of 1.22 at $k_s/k_g = 8000$. At an average multiplier region temperature of 400°C, k_s/k_g for the Be–He bed is about 422; from a thermal controllability point of view, this is very good.

(3) For all practical purposes, the thermal controllability is insensitive to the bed porosity.

(4) For $(r_c/r_p)^2 < 10^{-4}$, the thermal controllability remains constant at about 1.5 when the contact area between the particles increases. For $(r_c/r_p)^2 > 10^{-4}$, however, the thermal controllability decreases with the particle-to-particle contact area, and has a value of about 1.2 at $(r_c/r_p)^2 = 10^{-3}$.

(5) For r_1/r_2 values of 0.2, 0.1 and 0.05, the thermal controllability increases to 1.45, 1.47 and 1.49 as the roughness height δ increases from 0 to 0.4, 1.0 and 2 μm respectively. The thermal controllability decreases to 1.28, 1.35 and 1.42 as the surface roughness is increased to 5 μm.

A comparison of various bed effective thermal conductivity models with the UCLA experimental data was carried out in Section 4. The modified Hall–Martin model (UCLA version) can reproduce the experimental data reasonably well with an artificially large contact area. The SZB model overpredicts the Be–He data and underpredicts the Be–N_2 experimental data. With an artificially empirical large particle-to-particle contact area, the SZB model can reproduce the UCLA Be–N_2 experimental data. The Kunii–Smith model is not suitable for estimating the Be–He and Be–N_2 (high solid-to-gas thermal conductivity ratio) particle bed. The UCLA 2-D model is the favorite model in the group. It reproduces the test results for tests 1–3 (Be–He particle bed) reasonably well when using realistic parameters. However, it cannot reproduce result for test 4 (Be–N_2 particle bed) using the same physical parameters.

The comparison of the models with the UCLA experimental data shows that the best model for predicting the Be–He particle bed for the test case considered is the UCLA 2-D model, in which a realistic contact area is used while other models may use a large contact area to offset the error caused by the 1-D assumption; otherwise, the model cannot give reasonable predictions.

The modified Hall–Martin model (UCLA version) is a good model to estimate the particle bed thermal conductivity. However, an articficially large contact area parameter must be used to compensate for the error caused by the one-dimensional heat transfer assumption. Before using the modified Hall–Martin model, reliable experimental data are needed as a benchmark to obtain the empirical contact area.

In this paper, the experimental data used were only for Be–He or Be–N_2 single-size beds. The particle diameter was 2 mm. Further experiments should be carried out to study beryllium binary-packed beds.

Appendix A: Nomenclature

D_p	particle diameter (m)
f_{cor}	correction factor for bed porosity deviating from 0.3333
g	jump distance (m)
k_{eff}	effective thermal conductivity of the packed bed ($\mathrm{W\,m^{-1}\,K^{-1}}$)
k_g	gas thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
k_H	effective conductivity of the void space ($\mathrm{W\,m^{-1}\,K^{-1}}$)
k_s	solid thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
r_b	particle radius in heat flow direction (m)
r_c	contact radius (m)
r_f	radius not occupied by fine particles in binary packing (m)
r_p	particle radius (m)
$(r_1/r_2)^2$	the fraction of the particle surface area covered by roughness
T	average bed temperature (K)
TAC	thermal accomodation coefficient of the cover gas on the particle surface
TAC_0	TAC of ideal smooth surface
t_{gap}	separation distance between spheres (m)
z_r	shape factor

Greek letters

ϕ_c	contact angle (rad)
λ_0	gas molecule mean free path length (m)
δ	area fraction of solid–solid conduction path of SZB model (m)
Δ	roughness height (m)
ε	bed porosity
ξ_r	particle size distribution
ξ_1	coefficient of variation of the particle size distribution

Subscripts

f	fine particle in binary packing
l	large particle in binary packing

References

[1] R.O.A. Hall and D.G. Martin, The thermal conductivity of power beds. A model, some measurements on UO_2 vibro-compacted microspheres, and their correlation, J. Nucl. Mater., 101 (1981) 172–183.

[2] M.A. Abdou et al., Thermal, fluid flow and tritium release problems in fusion blankets, Fusion Technol., 18 (1990) 165–200.

[3] A.R. Raffray and M. Zu, Packed bed effective thermal conductivity based on modified Hall and Martin expression, Rep. UCLA-FNT-49, 1991.

[4] R.K. McGeary, Mechanical packing of spherical particles, J. Am. Ceram. Soc., 44 (1961) 513–522.

[5] M.D. Donne and G. Sordon, Heat transfer in pebble beds for fusion blankets, Fusion Technol., 17 (1990) 597–635.

[6] R. Bauer and E.U. Schlunder, Effective radial thermal conductivity of packings in gas flow. Part I. Convective transport coefficient, Verfahrenstechnik, 11 (1977) 181–188.

[7] R. Bauer and E.U. Schlunder, Effective radial thermal conductivity of packings in gas flow. Part II. Thermal conductivity of the packing fraction without gas flow, Verfahrenstechnik, 11 (1977) 189–204.

[8] J.S.M. Botterill, A.G. Salway and Y. Teoman, The effective thermal conductivity of high temperature particulate beds—II. Model predictions and the implication of the experimental values, Int. J. Heat Mass Transfer, 32 (1989) 595–609.

[9] P. Adnani, Modeling of transport phenomena in porous media, Ph.D. Dissertation, University of California, Los Angeles, CA, 1991.

[10] D. Kunii and J.M. Smith, Heat transfer characteristics in porous rocks, AIChE J., 6 (March 1960) 71–78.

[11] M. Xu, Analysis of the thermal conductivity of beryllium-gas packed beds, Master Thesis, University of California, Los Angeles, CA, 1993.

[12] Personal communication with Mark S. Tillack, UCLA, 1992–93.

[13] F. Tehranian, M.A. Abdou and M.S. Tillack, Effect of external pressure on particle bed effective thermal conductivity, J. Nucl. Mater., in press.