ANALYSIS AND PARAMETRIC STUDY OF SINGLE-SIZED GAS-SOLID PARTICLE BEDS

Mohamed M. Elafify and Alya A. Badawi
Nuclear Engineering Department, Faculty of Engineering,
Alexandria University, Alexandria, Egypt.

ABSTRACT

Packed beds have a variety of common applications in nuclear engineering. It has been proposed for usage in fuel and blankets in some reactor types. Throughout this research, an analysis of the effect of various parameters on the effective thermal conductivity of a packed bed is performed. In particular, the effects of cover gas pressure, size of solid spheres and contact area between particles, are discussed in details. These parameters can be controlled during fabrication and/or operation. The gas and solid thermal conductivities, however, are usually predetermined by the choice of material and, therefore, their effects were not studied in great detail. Throughout this research different materials are used for both solid spheres and cover gas. For solid spheres copper, aluminum, and uranium dioxide are used, while for cover gases helium and nitrogen are used.

Keywords: Particle beds, Thermal conductivity, Gas pressure, Contract area.

INTRODUCTION

Packed beds are being used in a wide variety of applications. Particle beds of (U,Pu)O_2 spheres have been proposed for use as fuel in fast breeder reactors [1]. In fusion reactors, packed beds of lithium ceramics have been suggested as solid breeders in the blanket [2-5]. A Be packed bed between the high temperature breeder and low temperature coolant has also been proposed for an ITER solid breeder base blanket in order to provide a controlled thermal resistance between the coolant which is kept at moderate temperature for safety considerations and the solid breeder which is kept at high temperature to allow for tritium release [6,7]. Accurate knowledge of the thermal behavior, and in particular the thermal conductivity, of packed beds is therefore required for the design and analysis of such systems.

The variation in the thermal conductivity of packed beds with different parameters have been investigated. Raffray et al. [8] studied the effects of gas pressure, contact area between spheres and roughness characteristics of the surface, using a 2-D model that calculates the thermal conductivity of a spherical unit cell numerically [9]. The effect of thermal conductance of bed walls was also studied for different packed bed designs. Gorbis [10] studied the effects of the same parameters on the bed thermal conductivity. However, he used a 1-D model that divides the unit cell into different zones, each having a characteristic thermal resistance. Swift [11] investigated the variation of the thermal conductivity with gas pressure, temperature and particle size using orthorhombic unit cell with linear heat flow. He also studied the effect of oxide coating. Swift found that the thermal conductivity increases with increasing the gas temperature and/or pressure. Its value was found to decrease with increasing the amount of oxide layer. Bauer and Schlinder [12] studied the effect of gas pressure, contact area between solid spheres and oxidization of the spheres, both experimentally as well as theoretically using semiemperical equations. They reached to conclusions similar to Swift's.

A model was presented which predicts the conductivity of packed beds based on solving the 2-D heat conduction equation in a cylindrical unit cell [13]. The steady state 2-D heat conduction equation in cylindrical coordinates can be applied to the unit cell;

$$\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)=-\dot{q} \quad (1)$$

where k is the thermal conductivity of either the solid or the gas, depending on the region in which the equation is applied, and $\dot{q}$ is the volumetric heat generation source strength.

The equation is solved using the finite element method with the following boundary conditions [14]

$$T = T_1 \quad \text{at } z = 0 \quad (2)$$

$$T = T_2 \quad \text{at } z = 2r_s \quad (3)$$

$$\frac{\partial T}{\partial r} = 0 \quad \text{at } r = 0 \quad (4)$$

$$\frac{\partial T}{\partial r} = 0 \quad \text{at } r = r_s + a \quad (5)$$

where r_s is the sphere radius and (a) is a parameter to account for the bed porosity. The effective thermal conductivity of the bed is calculated using the heat flux, q_{uc}, passing through the unit cell [13]

$$k_{eff} = \frac{q_{uc}(2r_s)}{A_{uc}(T_1 - T_2)} \quad (6)$$

where A_{uc} is the unit cell cross sectional area. A computer finite element code, based on the model, was developed and verified [13]. This code is used throughout this paper to investigate the effect of different parameters on the effective thermal conductitity of the packed bed.

FACTORS THAT CONTROL THE EFFECTIVE THERMAL CONDUCTIVITY OF PARTICLE BEDS

To determine the factors that control the magnitude of the thermal conductivity in particle packed beds, consider a qualitative representation of a unit cylindrical cell. The heat flow through the cell can be represented qualitatively by three thermal resistances in parallel. The first resistance to account for heat flow in solid only through contact areas between spheres. The thermal conductance of such resistance is C_s. This resistance vanishes for zero touch area sphere beds. The second resistance to account for heat flow through combined gas and solid domains. The thermal conductance of such resistance is given by

$$C_c = C_{s1}\, C_{g1}/(C_{s1}+C_{g1}) \quad (7)$$

The third resistance accounts for heat flow through cover gas only. The thermal conductance of the last resistance is C_g. The overall thermal conductance of a unit cell is given by

$$C_{uc} = C_s + C_c + C_g \quad (8)$$

Differentiating ;

$$\delta C_{uc} = \delta C_s + \delta C_c + \delta C_g \quad (9)$$

$$\delta C_{uc} = \delta C_s + \{C_{g1}^2/(C_{s1}+C_{g1})^2\}\delta C_{s1} + \{C_{s1}^2/(C_{s1}+C_{g1})^2\}\delta C_{g1} + \delta C_g \quad (10)$$

As a result of previous simple analysis, the effective thermal conductivity of a packed bed is found to be a function of the parameters that control C_s, C_g, C_{s1} and C_{g1}. These parameters are:

1. Gas pressure
2. Gas thermal conductivity
3. Solid thermal conductivity
4. Size of solid spheres,
5. Contact area between solid spheres

The first and second parameters affect C_{uc} through their effect on C_g and C_{g1}, while the rest of the parameters affect C_s and C_{s1}. A parametric study of these factors are going to be presented in the following sections.

EFFECT OF GAS PRESSURE

As a result of the simplified analysis given above, the effect of pressure on C_{uc} can be represented by:

$$(\delta C_{uc}/\delta P)=(\delta C_s/\delta P)+\{C_{s1}^2/(C_{s1}+C_{g1})^2\}(\delta C_{g1}/\delta P) \quad (11)$$

This simple analysis shows that it is possible to control the effective thermal conductivity of the particle bed by changing the cover gas pressure [8,15].

Figure (1) shows the effect of increasing the gas pressure on the effective thermal conductivity for packed beds of Cu/He, Al/He, and UO_2/He. In order to eliminate the effect of other parameters on the effective thermal conductivity, the three beds have the same sphere diameter (0.721mm), porosity (0.384) and average unit cell temperature (320K). The figure shows that k_{eff} increases with increasing pressure in all cases. This can be explained by the fact that the thermal conductivity of the gas increases with increasing the pressure due the decrease of the Smoluchowski effect at high pressures (diminishing of Knudsen domain). The change in k_{eff} is more pronounced at low pressures as the gas thermal conductivity is highly affected by pressure changes at such pressures. As expected, the effective thermal conductivity is slightly higher in the case of Cu/He than Al/He due to the higher thermal conductivity of copper ($k_{Cu} : k_{Al} = 1.7:1$). The effective thermal conductivity of the UO_2/He bed is the lowest due to the low thermal conductivity of the UO_2. The difference in k_{eff} for the different solids is larger at high pressures than at low pressures. This behavior is explained by the fact that increasing pressure leads to an increase in the conductance of the gas. This conductance is scaled by the factor $\{C_{s1}^2/(C_{s1}+C_{g1})^2\}$ in the combined conductance term (see eq. (11)) leading to higher rate of increase in the overall effective thermal conductivity for high conducting solids. Therefore the amount of heat flowing through the gas in particle beds depends on the thermal conductivity of the solid.

In Figure (2) the effect of pressure on the effective thermal conductivity of Cu/N_2 and Al/N_2 beds is shown for beds of 0.721mm spheres at temperature 340K and porosity 0.384. Again, increasing the pressure increases k_{eff} in both cases. However, the values of k_{eff} in both cases are less than those found in Figure (1) for Cu/He and Al/He beds. This is due to the lower thermal conductivity of nitrogen compared to helium. Figures (1) and (2) show that k_{eff} increases with increasing the gas thermal conductivity. For copper spheres, k_{eff} at 3atm is equal to 3.062 W/mK for the case of helium cover gas, while it is equal to 1.837 W/mK for the case of nitrogen cover gas.

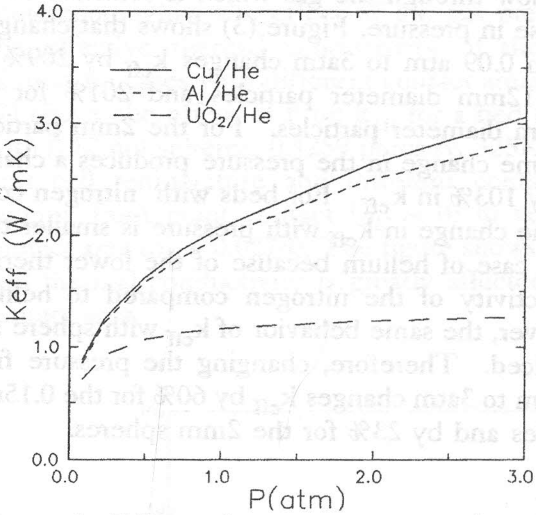

Figure 1. Effect of gas pressure on the effective thermal conductivity of a packed bed with helium cover gas and different solids.

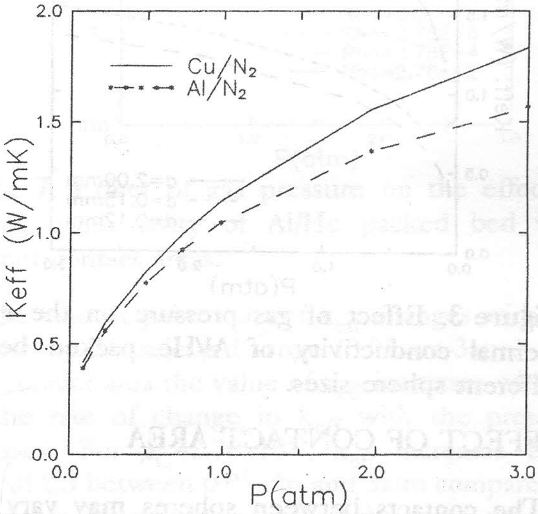

Figure 2. Effect of gas pressure on the effective thermal conductivity of a packed bed with nitrogen cover gas and different solids.

EFFECT OF THE SPHERE SIZE

Figures (3) and (4) show the change in k_{eff} with pressure for packed beds of aluminum with various sphere sizes. The cover gas in Figure (3) is helium, while it is nitrogen in Figure (4). Increasing the sphere size leads to a decrease in the rate of change in k_{eff} with pressure. This can be attributed to the increase in the heat flow through the larger spheres.

Thus, small size spheres cause an increase in the heat flow through the gas which is sensitive to the increase in pressure. Figure (3) shows that changing P from 0.09 atm to 3atm changes k_{eff} by 209% for the 0.12mm diameter particles and 201% for the 0.15mm diameter particles. For the 2mm particles the same change in the pressure produces a change of only 103% in k_{eff}. For beds with nitrogen cover gas, the change in k_{eff} with pressure is smaller than in the case of helium because of the lower thermal conductivity of the nitrogen compared to helium. *However, the same behavior of k_{eff} with sphere size is noticed. Therefore, changing the pressure from 0.09atm to 3atm changes k_{eff} by 60% for the 0.15mm particles and by 23% for the 2mm spheres.*

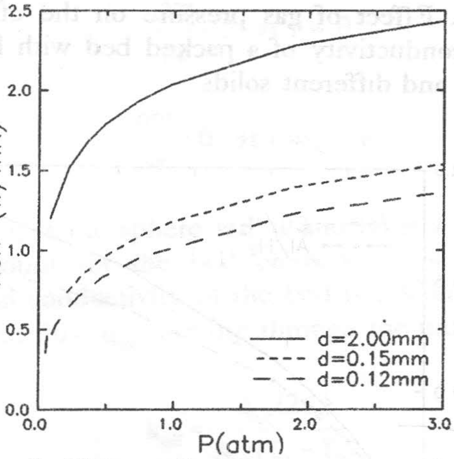

Figure 3. Effect of gas pressure on the effective thermal conductivity of Al/He packed bed with different sphere sizes.

EFFECT OF CONTACT AREA

The contacts between spheres may vary due to many factors. In an ideal case they are point contacts and the heat transfer takes place almost exclusively through the gas gap. However, due to the thermal expansion and irradiation swelling in the bed, a mechanical load on bed spheres may result in the presence of a contact area between the spheres [15].

Figure (5) shows the effect of increasing the contact area on the unit cell effective thermal conductivity for an Al/He packed bed with 0.12mm diameter spheres, 0.4259 porosity and 325K average unit cell temperature at 1atm and a bed of Cu/He with 0.721mm diameter spheres, 0.384 porosity, 321K average bed. Temperature at 1atm pressure. For both beds it is noted that even a small contact area seems to influence the thermal conductivity of the bed. In order to exclude the effect of sphere size, the contact area is represented by a parameter ρ_c defined as [12]

$$\rho_c = (r_c / r_s)^2 \tag{12}$$

where r_c is the contact radius.

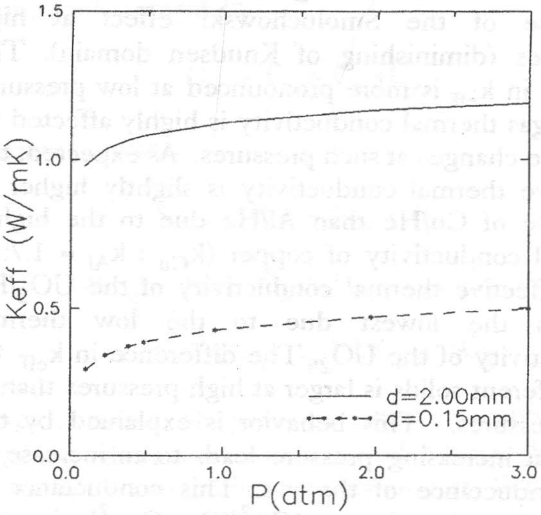

Figure 4. Effect of gas pressure on the effective thermal conductivity of an Al/N_2 packed bed with different sphere sizes.

In Figure (5), k_{eff} increases slowly with increasing ρ_c, for small values of ρ_c, then it starts to increase rapidly for large values of ρ_c. For the Al/He bed, increasing ρ_c from $2x10^{-6}$ to $4x10^{-6}$ (by a factor of 2) increases k_{eff} by a factor of 1.4, whereas increasing ρ_c from $2x10^{-5}$ to $4x10^{-5}$ (a factor of 2) increases k_{eff} by a factor of 1.7 . Increasing ρ_c from $2x10^{-4}$ to $4x10^{-4}$(again a factor of 2) increases k_{eff} by a factor of 1.9. This is attributed to the fact that the higher the contact area, the lower the heat flow through the cover gas, and the smaller the domain available for the Smoluchowski effect, which is mainly determined by the distance between spheres. It worth mentioning that although the effective thermal conductivity of the bed increases with increasing the contact area, its value will never reach the solid thermal conductivity due to the presence of the gas which will always force k_{eff} of a unit cell to have a lower value than k_{solid}. For the Cu/He bed, the values of k_{eff} are higher than those of the Al/He bed because of the higher thermal conductivity of copper. However, the same behavior is noticed. Increasing ρ_c causes an increase in the value of k_{eff}.

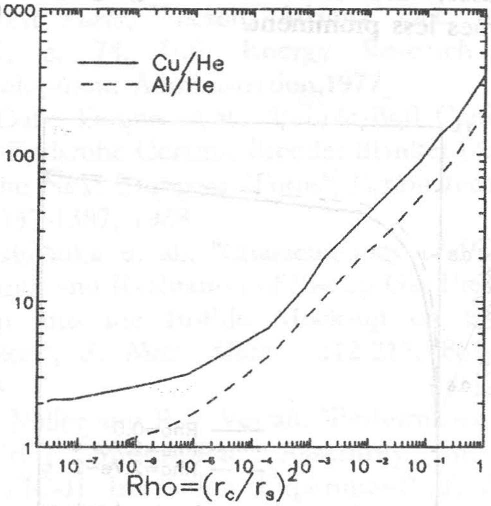

Figure 5. Effect of the area of contact on the effective thermal conductivity of Al/He and Cu/He packed beds at 1atm.

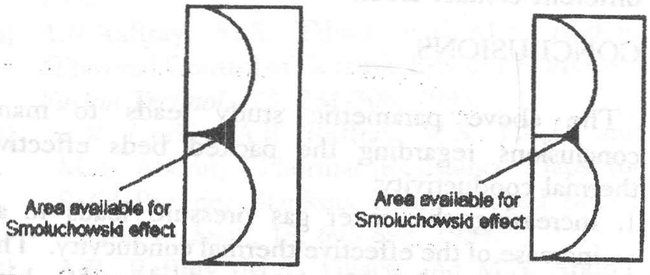

Figure 6. Schematic diagrams showing the effect of increasing the contact area on the area available for the Smoluchowski effect (a) point contact (b) large contact.

Figure (6) shows the effect of contact area on the Knudsen domain. In Figure (6a) there is almost no contact and the zone where the Smoluchowski effect takes place is large, since it is the area in which the vertical distance between the spheres is comparable to the mean free path of the gas molecules. In Figure (6b), the large contact area between the spheres diminishes Smoluchowski domain, leading to an additional increase in the value of k_{eff}.

In order to investigate the effect of the contact area more thoroughly, the effect of the gas pressure on the effective thermal conductivity of the bed is plotted for cases with different contact areas. Figure (7) shows the effect of P on k_{eff} for a bed of Al/He with 0.12mm spheres, 0.4259 porosity, 325K average unit cell temperature and different contact areas ranging from point contact ($\rho_C = 0$) to very large contact area ($\rho_C = 0.0278$). The figure shows that the bed thermal conductivity is greatly affected by the contact area.

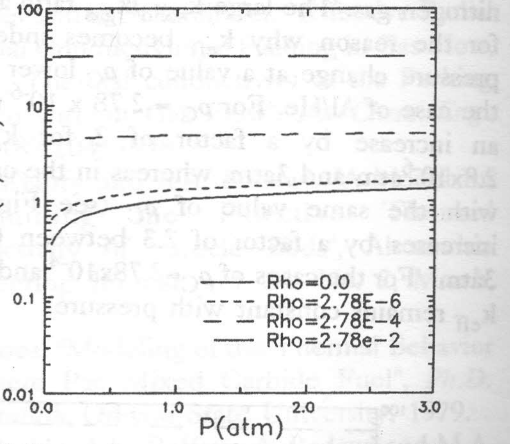

Figure 7. Effect of gas pressure on the effective thermal conductivity of Al/He packed bed with different contact areas.

In the case of point contact k_{eff} changes with the pressure in the selected range (0.05atm-3atm). For small contact area the value of k_{eff} increases with ρ_C and the rate of change in k_{eff} with the pressure decreases. For ρ_C=2.78x10^{-6}, k_{eff} increases by a factor of 2.3 between 0.05atm and 3atm compared to an increase by a factor of 3.3 in the same pressure range for the case with point contact. At 0.05atm, k_{eff} at ρ_C = 2.78 x 10^{-6} is about 1.7 times higher than that at $\rho_C = 0$, while it is about 1.2 times higher than that at $\rho_C = 0$ at 3atm. For large contact areas, k_{eff} starts to become independent of the gas pressure since most of the heat flows through the solid spheres. For the case of ρ_C=2.78x10^{-4}, k_{eff} changes by only 20% between 0.05atm and 3atm, while for the case of ρ_C=0.0278, k_{eff} remains constant with increasing pressure.

Figure (8) shows the effect of P on k_{eff} for a bed of Cu/ N_2 with 1.8mm diameter spheres, 0.39 porosity, 325K average unit cell temperature and

Thus, small size spheres cause an increase in the heat flow through the gas which is sensitive to the increase in pressure. Figure (3) shows that changing P from 0.09 atm to 3atm changes k_{eff} by 209% for the 0.12mm diameter particles and 201% for the 0.15mm diameter particles. For the 2mm particles the same change in the pressure produces a change of only 103% in k_{eff}. For beds with nitrogen cover gas, the change in k_{eff} with pressure is smaller than in the case of helium because of the lower thermal conductivity of the nitrogen compared to helium. However, the same behavior of k_{eff} with sphere size is noticed. Therefore, changing the pressure from 0.09atm to 3atm changes k_{eff} by 60% for the 0.15mm particles and by 23% for the 2mm spheres.

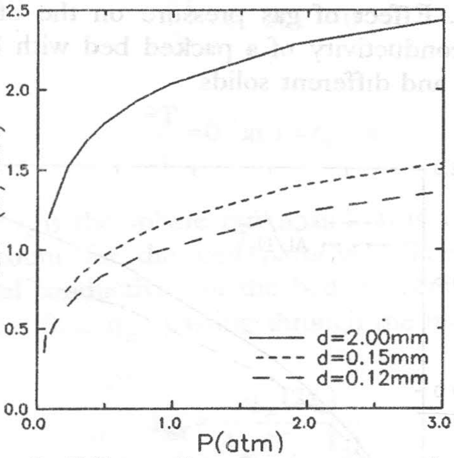

Figure 3. Effect of gas pressure on the effective thermal conductivity of Al/He packed bed with different sphere sizes.

EFFECT OF CONTACT AREA

The contacts between spheres may vary due to many factors. In an ideal case they are point contacts and the heat transfer takes place almost exclusively through the gas gap. However, due to the thermal expansion and irradiation swelling in the bed, a mechanical load on bed spheres may result in the presence of a contact area between the spheres [15].

Figure (5) shows the effect of increasing the contact area on the unit cell effective thermal conductivity for an Al/He packed bed with 0.12mm diameter spheres, 0.4259 porosity and 325K average unit cell temperature at 1atm and a bed of Cu/He with 0.721mm diameter spheres, 0.384 porosity, 321K average bed. Temperature at 1atm pressure. For both beds it is noted that even a small contact area seems to influence the thermal conductivity of the bed. In order to exclude the effect of sphere size, the contact area is represented by a parameter ρ_c defined as [12]

$$\rho_c = (r_c / r_s)^2 \qquad (12)$$

where r_c is the contact radius.

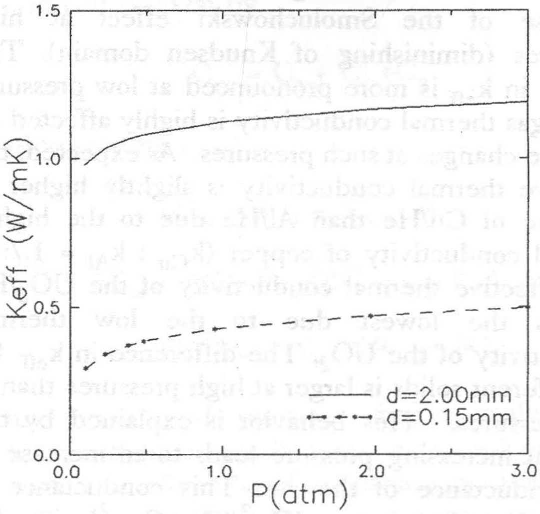

Figure 4. Effect of gas pressure on the effective thermal conductivity of an Al/N_2 packed bed with different sphere sizes.

In Figure (5), k_{eff} increases slowly with increasing ρ_c, for small values of ρ_c, then it starts to increase rapidly for large values of ρ_c. For the Al/He bed, increasing ρ_c from $2x10^{-6}$ to $4x10^{-6}$ (by a factor of 2) increases k_{eff} by a factor of 1.4, whereas increasing ρ_c from $2x10^{-5}$ to $4x10^{-5}$ (a factor of 2) increases k_{eff} by a factor of 1.7 . Increasing ρ_c from $2x10^{-4}$ to $4x10^{-4}$(again a factor of 2) increases k_{eff} by a factor of 1.9. This is attributed to the fact that the higher the contact area, the lower the heat flow through the cover gas, and the smaller the domain available for the Smoluchowski effect, which is mainly determined by the distance between spheres. It worth mentioning that although the effective thermal conductivity of the bed increases with increasing the contact area, its value will never reach the solid thermal conductivity due to the presence of the gas which will always force k_{eff} of a unit cell to have a lower value than k_{solid}. For the Cu/He bed, the values of k_{eff} are higher than those of the Al/He bed because of the higher thermal conductivity of copper. However, the same behavior is noticed. Increasing ρ_c causes an increase in the value of k_{eff}.

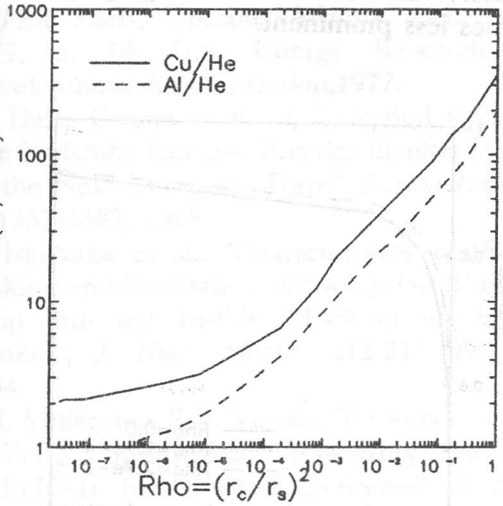

Figure 5. Effect of the area of contact on the effective thermal conductivity of Al/He and Cu/He packed beds at 1atm.

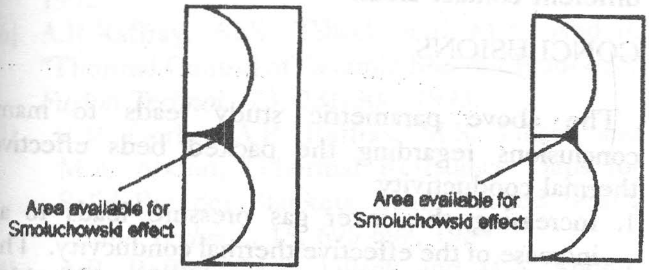

Figure 6. Schematic diagrams showing the effect of increasing the contact area on the area available for the Smoluchowski effect (a) point contact (b) large contact.

Figure (6) shows the effect of contact area on the Knudsen domain. In Figure (6a) there is almost no contact and the zone where the Smoluchowski effect takes place is large, since it is the area in which the vertical distance between the spheres is comparable to the mean free path of the gas molecules. In Figure (6b), the large contact area between the spheres diminishes Smoluchowski domain, leading to an additional increase in the value of k_{eff}.

In order to investigate the effect of the contact area more thoroughly, the effect of the gas pressure on the effective thermal conductivity of the bed is plotted for cases with different contact areas. Figure (7) shows the effect of P on k_{eff} for a bed of Al/He with 0.12mm spheres, 0.4259 porosity, 325K average unit cell temperature and different contact areas ranging from point contact ($\rho_C = 0$) to very large contact area ($\rho_C = 0.0278$). The figure shows that the bed thermal conductivity is greatly affected by the contact area.

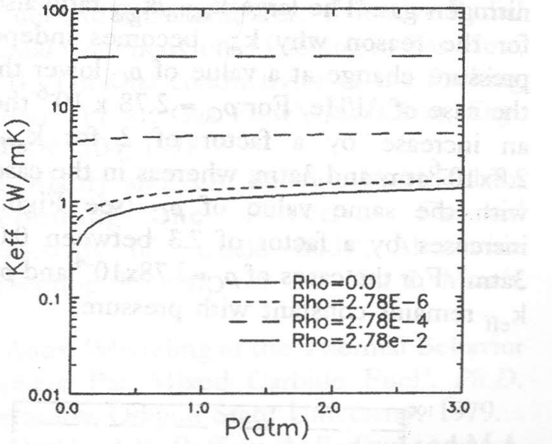

Figure 7. Effect of gas pressure on the effective thermal conductivity of Al/He packed bed with different contact areas.

In the case of point contact k_{eff} changes with the pressure in the selected range (0.05atm-3atm). For small contact area the value of k_{eff} increases with ρ_C and the rate of change in k_{eff} with the pressure decreases. For ρ_C=2.78x10^{-6}, k_{eff} increases by a factor of 2.3 between 0.05atm and 3atm compared to an increase by a factor of 3.3 in the same pressure range for the case with point contact. At 0.05atm, k_{eff} at ρ_C = 2.78 x 10^{-6} is about 1.7 times higher than that at ρ_C = 0 , while it is about 1.2 times higher than that at ρ_C = 0 at 3atm. For large contact areas, k_{eff} starts to become independent of the gas pressure since most of the heat flows through the solid spheres. For the case of ρ_C=2.78x10^{-4}, k_{eff} changes by only 20% between 0.05atm and 3atm, while for the case of ρ_C=0.0278, k_{eff} remains constant with increasing pressure.

Figure (8) shows the effect of P on k_{eff} for a bed of Cu/ N_2 with 1.8mm diameter spheres, 0.39 porosity, 325K average unit cell temperature and different contact areas ranging from point contact (ρ_C=0) to very large contact area (ρ_C=0.0278). In this figure k_{eff} is calculated starting from much lower pressure compared to that in Figure (7) in order to examine the effect of contact area at very low pressures. Again the cell effective thermal conductivity is found to be greatly affected by the change in contact area. However, for the case of Cu/ N_2 the change in k_{eff} is less sensitive to pressure increase than that for the case of Al/He. This can be explained by the fact that the large k_{solid}/k_{gas} ratio ($\simeq$ 16,000) in the case of Cu/ N_2 forces the heat flow to pass through the copper spheres rather than nitrogen gas. The large k_{solid}/k_{gas} ratio also accounts for the reason why k_{eff} becomes independent of pressure change at a value of ρ_C lower than that in the case of Al/He. For ρ_C = 2.78 x 10^{-6} there is only an increase by a factor of 2 for k_{eff} between 2.8×10^{-6}atm and 3atm, whereas in the case of Al/He with the same value of ρ_C (see Figure 7), k_{eff} increases by a factor of 2.3 between 0.05atm and 3atm. For the cases of ρ_C=2.78×10^{-4} and ρ_C= 0.0278, k_{eff} remains constant with pressure.

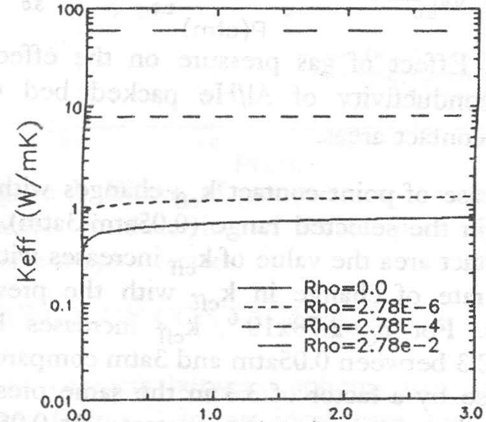

Figure 8. Effect of gas pressure on the effective thermal conductivity of a Cu/N_2 packed bed with different contact areas.

Figure (9) shows the effect of P on k_{eff} for a bed of UO_2/He with 0.04mm diameter spheres, 0.1933 packing fraction, 2500°C average cell temperature and different contact areas. In this figure k_{eff} is calculated up to high pressures in order to examine the effect of contact area at such pressures. Figure (9) represents the case of low k_{solid}/k_{gas} ratio ($\approx$50). In this case the bed thermal conductivity is found to be much less sensitive to the contact area than in the cases of aluminum and copper. The cases of point contact and ρ_C=2.78×10^{-4} produces almost the same results. In contrast to the cases of Cu/N_2 and Al/He, for the case of very large contact area (ρ_C=0.0278), k_{eff} increases with increasing pressure, leading to the conclusion that as the k_{solid}/k_{gas} ratio increases, the effect of changing gas pressure becomes less prominent.

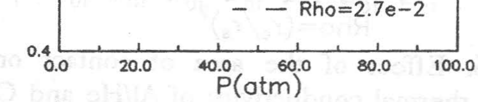

Figure 9. Effect of gas pressure on the effective thermal conductivity of a UO_2/He packed bed with different contact areas.

CONCLUSIONS

The above parametric study leads to many conclusions regarding the packed beds effective thermal conductivity:

1. Increasing the cover gas pressure leads to an increase of the effective thermal conducvity. The rate of increase in k_{eff} is higher for high conducting solids or high conducting gases.
2. Increasing the sphere size leads to a decrease in the rate of change in k_{eff} with pressure.
3. Increasing the contact area between spheres increases the effective thermal conductivity, but it never reaches value of the pure solid contact area due to the existence of gas in the representation of the equivalent unit cell.
4. As the contact area increases, k_{eff} becomes less sensitive to cover gas pressure increase. For high contact areas the cover gas pressure has no effect on the value of k_{eff} for high conductive solids (such as copper), while for low conductive solids

(such as UO_2) the pressure still affects k_{eff} even at high contact areas.

REFERENCES

[1] R.W. Stratton, "Development of Advanced Fuels in Switzerland", *Proc. Mtg. Advanced LMFBR Fuels*, Tucson, Arizona, Oct. 10-13, 1977, p. 74, U.S. Energy Research and Development Administration,1977.

[2] M. Dalle Donne et al., "Pebble-Bed Canister: The Karlsruhe Ceramic Breeder Blanket Design for the Next European Torus", *Fusion Technol.*, 14,1357-1387, 1988.

[3] E. Ishitsuka et al., "Characteristics of Pebble Packing and Evaluation of Sweep Gas Pressure Drop into the In-Pile Mock-up on Fusion Blanket", *J. Nucl. Mater.*, 212-215, 881-884, 1994.

[4] J.M. Miller and R.A. Verrall, "Performance of a Li_2ZrO_3 Sphere-Pac Assembly in the CRITIC-II Irradiation Experiment", *J. Nucl. Mater.*, 212-215, 897-901, 1994.

[5] H. Takatsu et al., "Layered Pebble Bed Concept for ITER Breeder Blanket", *Presented at 17th Symp. Fusion Technology*, Rome, Italy, 1992.

[6] A.R.Raffray, M.S. Tillack and M.A. Abdou, "Thermal Control of Ceramic Breeder Blankets", *Fusion Technol.*, 23, 281-308, 1993.

[7] Z.R. Gorbis, A.R. Raffray, M.S. Tillack and M.A. Abdou, "Thermal Resistance Gaps for Solid Breeder Blankets Using Packed Beds", *Fusion Technol.*, 15, 695-698, 1989.

[8] A.R. Raffray, M.S. Tillack and M.A. Abdou, "Thermal Control of Ceramic Breeder Blanket", *Fusion Technol.*, 23, 281-308, 1993.

[9] P. Adnani, A.R. Raffray, M.A. Abdou and I. Catton, "Modeling of Effective Conductivity for a Packed Bed", *UCLA-FNT-29*, University of California, Los Angeles Report, November 1989.

[10] Z. Gorbis, "Zone Model for Packed Bed Effective Thermal Conductivity", *UCLA-FNT-28*, University of California, Los Angeles Report, October 1989.

[11] D.L.Swift, "The thermal Conductivity of Spherical Metal Powder Inculding the Effect of an Oxide Coating", *Int. J. Heat Transfer*, 9, pp. 1061-1074, 1966.

[12] R. Bauer and E.U. Schlinder, "Effective Radial Thermal Conductivity of Packing in Gas Flow, Part II, Thermal conductivity of the Packing Fraction without Gas Flow", *Int. Chem. Eng.*, 18, 2, 189-204, 1978.

[13] M.M. Elafify and A.A. Badawi, "A Model for Determining the Effective Thermal Conductivity of Particle Beds", Alexandria Engineering Journal, vol. 36. No. 2, March, 1997.

[14] M.J. Ades, "Modeling of the Thermal Behavior of Sphere Pac Mixed Carbide Fuel", *Ph.D. Dissertation*, Oregon State University, 1979.

[15] Z.R. Gorbis, A.R. Raffray, A. Badawi and M.A. Abdou, "Parametric Analysis of Packed Bed Effective Conductivity Using Zone Model", *UCLA-FNT-38*, University of California, Los Angeles Report, March 1990.

[16] F. Tehranian and M.A. Abdou, " Experimental Study of the Effect of External Pressure on Particle Bed Effective Thermal Properties", *Fusion Technol.*, 27, 298-313, 1995.