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Effect of external pressure on particle bed effective thermal conductivity

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Abstract

Accurate prediction of the thermomechanical responses of particle beds in fusion blankets depends strongly on the availability of experimental data on their thermal properties as a function of the blanket operating conditions. In this study, a series of experiments was conducted to measure the effective conductivity and interface conductance of singe-size aluminum, beryllium and lithium zirconate particle beds as a function of applied external load in the range 0–1.6 MPa. Experiments were carried out with both helium and air as cover gas over a range of pressure 30–760 Torr. In both aluminum and beryllium beds, as the applied load was increased to 1.5 MPa, the effective thermal conductivity increased by a factor of ~3–7 in an air cover gas, and a factor of ~2–3 in helium. With 1.2 mm lithium zirconate particles and air as the cover gas, changes in the bed thermal conductivity when the applied load was varied in the range of 0–1.6 MPa were small and within the experimental error. The increase in the interface conductance values with applied external load shows variations similar to those of the thermal conductivity.

1. Introduction

Particle beds have been considered as an alternative to liquid metals and solid blocks for use as breeder and multiplier materials in the blanket of fusion reactors [1–4]. Knowledge of the effective bed thermal conductivity and bed/clad interface thermal conductance coefficient is essential in the design and analysis of such systems. Unlike solid blocks, pebble beds are sensitive to several operating conditions. In addition to temperature, bed conductivity and wall conductance depend on the cover gas composition and pressure, and the internal stress state of the bed. These dependencies can be utilized to provide more robust thermal performance, or even actively control temperature profiles during operation [5,6].

Much effort has been devoted by different groups [7–10] to model the thermal conductivity and interface conductance coefficient of packed particle beds over the last several years with great success. The available models are capable of predicting thermal properties of single size and binary packed beds as a function of the controlling parameters such as the solid to gas conductivity ratio, cover gas and cover gas pressure, surface roughness and the particle-to-particle contact area. The value of the particle to particle contact area, has usually been assumed either zero (point contact assumption) or used as a parameter for benchmarking the models with the available experimental data. The actual value of the particle-to-particle contact area, however is a function of the contact pressures between particles which in turn depend on the magnitude of the mechanical loads that the particle bed is subjected to. The mechanical loads could result, for example, due to the thermal expansion mismatch between the bed and the clad or irradiation swelling of the bed. Depending on the stiffness of the clad, high pressure coolants could also apply significant load on the particle bed.

In this study a series of experiments was performed in which the effective bed thermal conductivity as a function of the applied external pressure was measured. Measurements were performed for aluminum, beryllium and lithium zirconate single size particle beds. The choices of beryllium and lithium zirconate particle beds were based on their possible use as multiplier and breeder materials in fusion blankets. Alu-

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minum particle bed was chosen to study the high temperature effects while avoiding the problems associated with beryllium toxicity. For some cases, based on the measured values of the effective bed thermal conductivities, the interface conductance coefficient between the particle bed and the stainless steel surface, as a function of the applied external loads, were obtained.

2. Experimental

2.1. Experimental setup

The experimental apparatus allows control of the cover gas composition and pressure, the heat flux, and the vertical force applied to the bed. Control of the background gas is obtained using a vacuum bell jar pumped with a mechanical fore pump and back-filled with air, N_2 or He. Heating of up to 500 W is applied using a cable heater attached to a copper heating block. The heat then passes through a 2.54 cm rod for measuring the heat flux, through the specimen region, through another heat flux rod and then into the water coolant. Forces are applied with a 12-ton hydraulic press and measured with a standard load cell. Instrumentation includes thermocouples along the heat flux rod and in the bed, gas pressure gages, and the load cell.

2.2. Test article configuration

The test article consists of a cylindrical column of single size particles contained in an alumina insulating tube which is 5 cm long and has an inside diameter of 2.54 cm. The wall thickness of the tube is 1.27 cm. The alumina container has a thermal conductivity of ~ 0.09 W/m K at 500°C and a compressive strength of ~ 3.4 MPa normal to the thickness. The low conductivity insulating container is used to minimize the lateral heat losses and therefore the uncertainty in the measured heat fluxes. The heat flux through the test article is measured by a 2.54 cm diameter stainless steel heat flux meter located on the top of the bed. The temperatures through the bed are measured at four locations. The full description of the test article and its integration with the experimental setup is given in ref. [11].

2.3. Particle bed materials

Fig. 1 shows the scanning electron micrographs of the particles used in these experiments. Aluminum and lithium zirconate particles were granular with average diameters of 0.8 and 1.2 mm respectively. The beryllium particles were spherical with an average diameter of 2 mm and surface roughness of ~ 1 μm. The beryllium particles were obtained from Brush Wellman. The lithium zirconate particles were fabricated at Chalk River Laboratories in Ontario and provided by

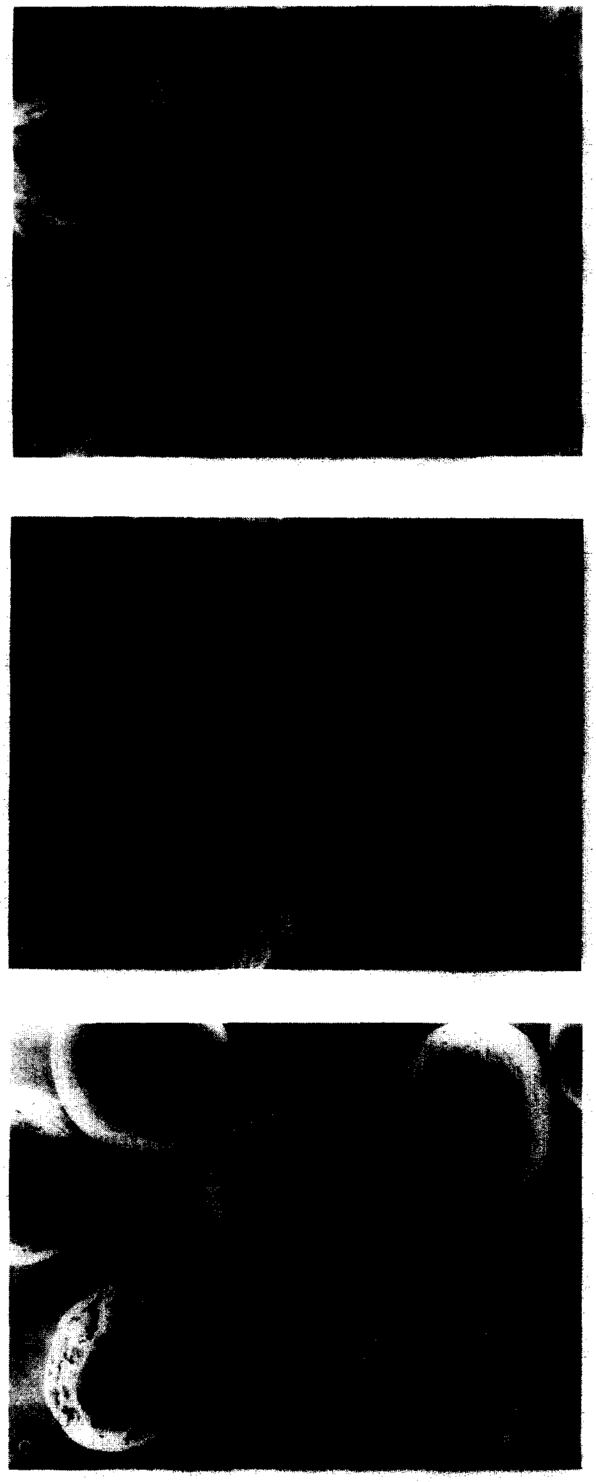

Fig. 1. Scanning electron micrographs of (a) aluminum, (b) lithium zirconate, and (c) beryllium particles.

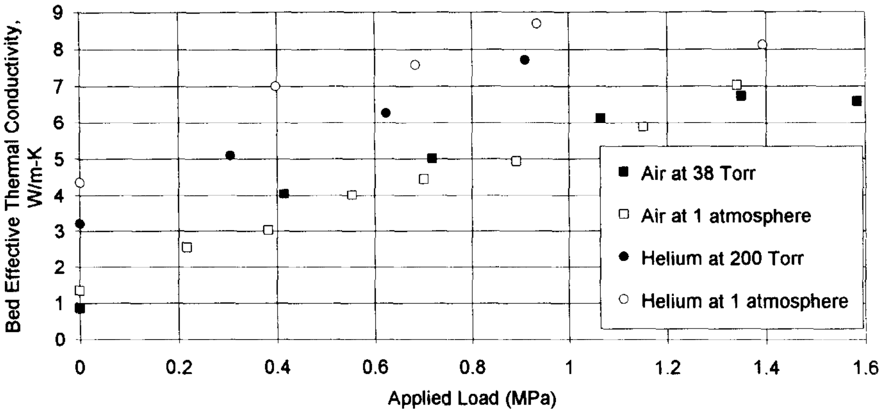

Fig. 2. Effect of external load on aluminum particle bed effective thermal conductivity; particle diameter = 0.8 mm, packing fraction = 0.63, average bed temperature = 29°C.

the Canadian Fusion Fuels Technology Project (CFFTP). The low-purity granular aluminum particles were fabricated by chip attrition.

3. Results and discussions

Based on the measured weight and volume of the particle beds, the packing fractions of the aluminum, beryllium and lithium zirconate beds were calculated to be 63%, 63% and 69.5% respectively.

3.1. Aluminum bed effective thermal conductivity

Fig. 2 shows the variation in the bed effective thermal conductivity as a function of applied external load, and air and helium as the cover gas. The effective thermal conductivity of aluminum particle bed, with air at atmospheric pressure as the cover gas, increased by a factor of 5.2 as the applied load was increased from zero to ~ 1.36 MPa. For the same range of the applied load (0 to 1.36 MPa), with air at 38 Torr pressure, the bed effective thermal conductivity increased by a factor of ~ 7.7. With helium at 1 atm and 200 Torr pressures, an increase in the applied load from zero to 1 MPa, increased the bed effective thermal conductivity by a factor of 1.86 and 2.4, respectively. It is clear that the increase in the bed effective thermal conductivity, due to the applied external load, is a strong function of the solid-to-gas conductivity ratio.

3.2. Beryllium bed effective thermal conductivity

The results of the measurements on the beryllium bed effective thermal conductivity as a function of applied load, shown in Fig. 3, are similar to those of the aluminum particle bed. The bed effective thermal conductivity, with air at atmospheric pressure as the cover gas, increased by a factor of 4.64 as the applied pressure was increased from zero to ~ 1.22 MPa. For

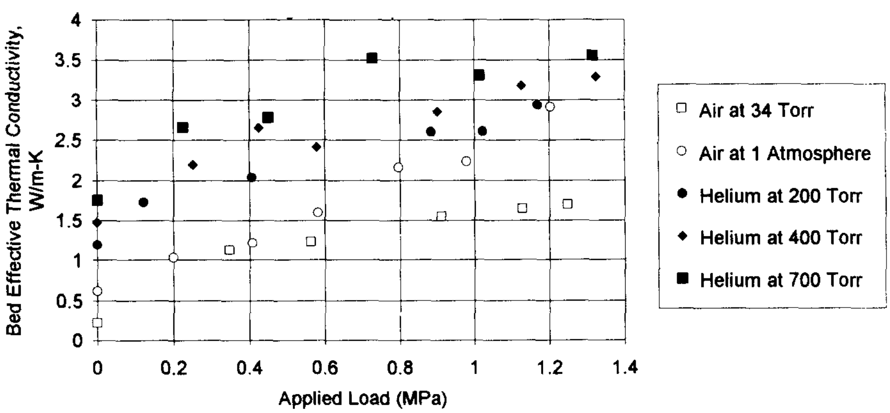

Fig. 3. Effect of external load on beryllium particle bed effective thermal conductivity; particle diameter = 2 mm, packing fraction = 0.634, average bed temperature = 33°C.

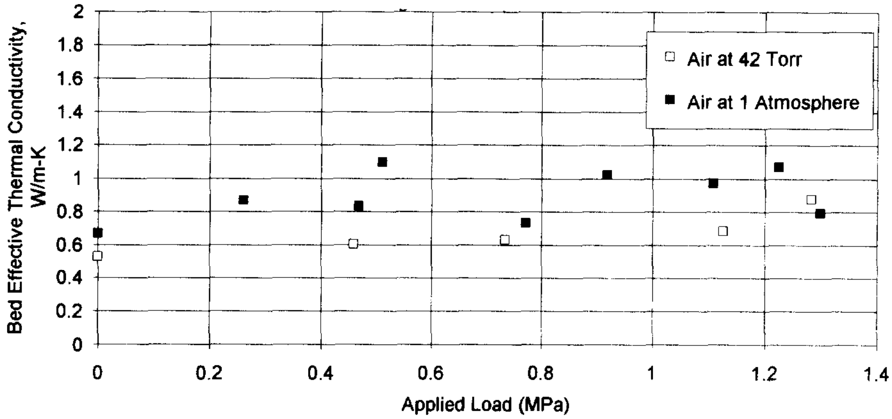

Fig. 4. Effect of external load on lithium zirconate particle bed effective thermal conductivity; particle diameter = 1.2 mm, packing fraction = 0.695, average bed temperature = 31°C.

the same range of the applied load (zero to 1.22 MPa) and air at 34 Torr, the bed effective thermal conductivity increased from 0.23 to ~ 1.7 W/m K i.e. by a factor of 7.4. With helium at 700, 400 and 200 Torr, increasing the applied load from zero to 1.22 MPa, increased the bed effective thermal conductivity by a factor of ~ 2, 2.2 and 2.46, respectively.

3.3. Lithium zirconate bed effective thermal conductivity

Fig. 4 shows the measured lithium zirconate particle bed effective thermal conductivity as a function of the applied load. With air at 1 atm and 42 Torr pressures as the cover gas and applied loads in the range of 0–1.7 MPa, the change in the bed effective thermal conductivity appears to be small and within the experimental error.

Table 1 shows the effect of external load on bed effective thermal conductivity for an arbitrary reference load value of 0.68 MPa. In this table, the thermal conductivity ratio, defined as the bed thermal conductivity when subjected to an external load divided by the bed thermal conductivity at no load, for the three particle bed materials and as a function of the cover gas pressure is given. For aluminum and beryllium beds with high solid thermal conductivity (therefore high solid-to-gas conductivity ratio), the increase in the bed effective thermal conductivity, due to the applied external load, varies from 1.72 with atmospheric helium as the cover gas to 5.8 with air at 34 Torr as the cover gas. For lithium zirconate particles, on the other hand, with a much lower solid thermal conductivity, the bed effective thermal conductivity is practically independent of the external load.

Also given in table 1 are the measured effective thermal conductivities of the three particle beds, with no external load, as a function of the cover gas pressure. These values are in good agreement with the unpublished data obtained by Paul Gierszewski at CFFTP [12].

3.4. Particle bed / stainless steel interface thermal conductance coefficient

Figs. 5 and 6 show the effect of applied external load on the bed/SS interface thermal conductance

Table 1
Thermal conductivity ratios [a,b] of aluminum, lithiium zirconate and beryllium particle beds subjected to an external pressure of 0.68 MPa

Particle type	Air cover gas pressure (Torr)					Helium cover gas pressure (Torr)			
	34	38	200	700	760	200	400	700	760
Aluminum		5.5 (0.9)			3.3 (1.35)	2.04 (3.2)			1.72 (4.4)
Beryllium	5.8 (0.25)		3.1 (0.6)		2.95 (0.65)	1.96 (1.2)	1.72 (1.72)	1.93 (1.76)	
Lithium zirconate		~ 1.04 (0.53)			~ 1.1 (0.67)				

[a] $(k)_{\text{with load}}/(k)_{\text{no load}}$
[b] Values in brackets: Measured conductivity at no load in W/m K.

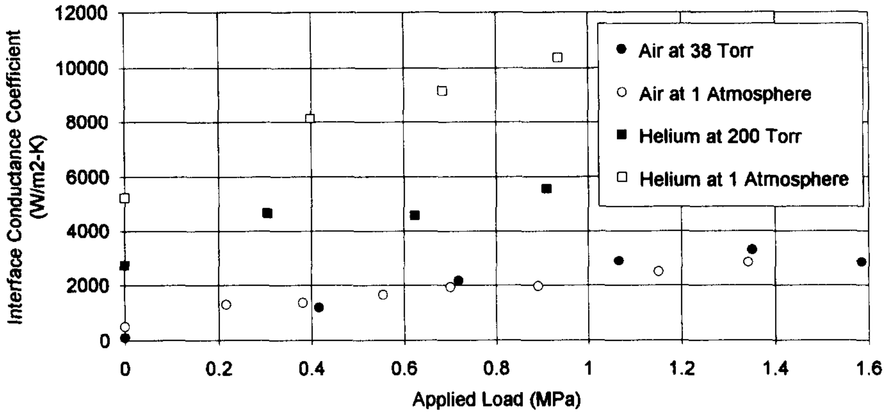

Fig. 5. Effect of external load on aluminum particle bed/SS surface interface conductance coefficient; particle diameter = 0.8 mm, packing fraction = 0.63.

coefficient. As in the case of bed thermal conductivity, the bed/wall interface thermal conductance coefficient is a strong function of the solid-to-gas conductivity ratio. For aluminum with high solid thermal conductivity, Fig. 5 shows that an increase in the applied load from zero to 1 MPa increases the interface thermal conductance coefficient by a factor of ~ 2 with helium as the cover gas and by a factor of ~ 10 with air as the cover gas. For lithium zirconate bed with much lower solid thermal conductivities, Fig. 6 shows that the increase in the interface thermal conductance coefficient, for applied loads in the range of 0–1.36 MPa, is small and within the experimental error.

4. Conclusions

The effective bed thermal conductivities of aluminum, beryllium and lithium zirconate particles with average respective diameters of 0.8, 2 and 1.2 mm, as a function of applied external load in the range of 0–1.5 MPa were measured. Air and helium at pressures in the range of 34 to 760 Torr were used as the cover gas. The following conclusions were reached:

When subjected to an external load of 1.36 MPa, with air at 1 atm and 38 Torr pressures, the aluminum bed effective thermal conductivity increased by factors of 5.2 and 7.7 respectively relative to the zero load. With helium at 1 atm and 200 Torr pressures, increasing the applied load from zero to 0.95 MPa, increased the effective aluminum bed thermal conductivity factors of 1.86 and 2.4, respectively.

The effective thermal conductivity of beryllium particle bed with air at 1 atmosphere pressure increased by a factor of 4.64 as the applied external load was raised from zero to 1.22 MPa. For the same range of the applied load (0 to 1.22) and air at 34 Torr, the bed effective thermal conductivity increased by a factor of ~ 7.4. With helium at 700, 400 and 200 Torr pressures, increasing the applied load from zero to 1.3 MPa, increased the beryllium bed effective thermal conductivity by a factor of 2, 2.24 and 2.44, respectively.

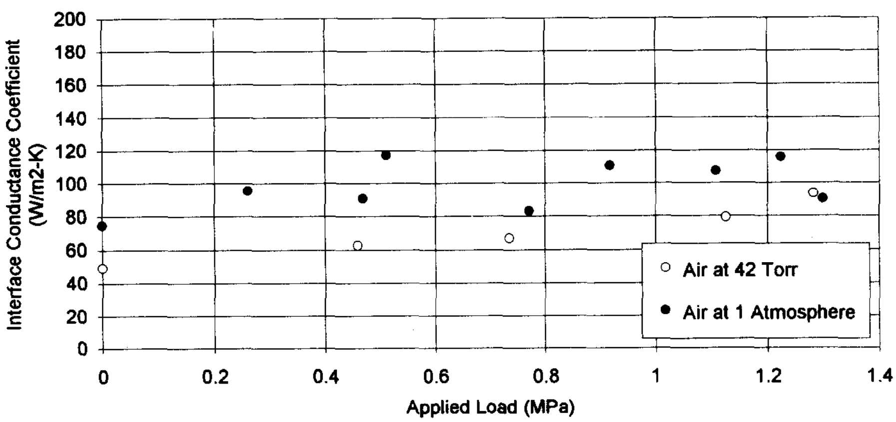

Fig. 6. Effect of external load on lithium zirconate particle bed/SS surface interface conductance coefficient; particle diameter = 1.2 mm, packing fraction = 0.695.

The observed changes in the lithium zirconate bed (PF = 69.5%) effective thermal conductivity when subjected to external loads of up to 1.7 MPa with air as the cover gas appears to be small and within the experimental error.

Variations in the bed/stainless steel interface conductance coefficient with the applied external load followed closely those of the bed effective thermal conductivity.

In general, The effective thermal conductivity of packed beds increases when subjected to external mechanical loads. The degree of increase in the bed thermal conductivity with applied external load is a strong function of the solid-to-gas conductivity ratio.

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