EXPERIMENTAL INVESTIGATION AND ANALYSIS OF THE EFFECTIVE THERMAL PROPERTIES OF BERYLLIUM PACKED BEDS

A. ABOU-SENA, A. YING, and M. ABDOU
Mechanical and Aerospace Engineering Department, UCLA, Los Angeles, CA 90095-1597
ali@fusion.ucla.edu

ABSTRACT

Beryllium, in its pebble form, has been proposed in various blanket concepts to serve different purposes. Thermal property data for such a heterogeneous packed bed is needed, particularly data on the impact of compression forces on its magnitude and consequent temperature profile. The objectives of this work are to obtain and quantify experimental data on the effective thermal conductivity of a Be-He packed bed, on the interface heat conductance between Be and SiC, and on the effects of externally applied pressure on these effective thermal properties. The effective thermal conductivity of a Be-He pebble bed increases as the bed mean temperature increases. The values of effective thermal conductivity vary from 2.15 to 3.00 W/m.K for bed mean temperature ranges from 90 to 420°C. Similar temperature effects are seen in the Be/SiC interface heat conductance, as the values of interface heat conductance range from 1140 to 2200 $W/m^2.K$. In addition, effective thermal conductivity increases remarkably with the increase of applied pressure (by a factor of 2.53 at 2 MPa), while it remains higher than the initial value by ~0.3 W/m.K when external pressure is released (hysteresis effect).

I. INTRODUCTION

Beryllium (as a neutron multiplier) is considered one of the prime candidates to enhance tritium breeding in the blanket. The key features of beryllium are its effective high neutron multiplication cross-section, high thermal conductivity, low density and low activation properties. However, the major difficulties with using beryllium are radiation induced swelling, the relatively low melting temperature, high sputtering rate, toxicity, and tritium retention characteristics. The Helium Cooled Pebble Bed (HCPB) blanket, proposed by the European Community for a Demonstration Reactor (DEMO), is based on using ceramic breeder pebble beds and beryllium pebble beds as a neutron multiplier. Also, pebble beds have been suggested as a material form for the blanket of ITER (International Thermonuclear Experimental Reactor). Beryllium is used in the form of a packed pebble bed where temperature control is required because the pebble bed thermal conductivity could be controlled through adjusting purge gas compositions and operating ranges. In general, the pebble bed can be treated as an homogeneous medium and the heat transfer parameters can be reduced to two coefficients: the effective thermal conductivity of the bed and the heat transfer coefficient at the bed container walls.

Knowledge of the bed effective thermal conductivity and the bed-clad interface thermal conductance coefficient is important for the design and analysis of fusion blankets. The thermal behavior of the bed as a blanket subsystem affects the overall performance of the blanket because the effective thermal conductivity of the bed affects the rate of heat transfer through the blanket. It has been shown in previous investigation,[1] that the effective thermal conductivity depends on particle size and roughness, particle-to-particle contact area, cover gas type and its pressure, packing fraction, solid-to-gas conductivity ratio and external applied pressure. These dependencies can help to control and predict the temperature profiles of the blanket during operation. In fact this is not an easy task because many of these parameters are strongly interconnected and affect each other.

During blanket operation, stresses are developed by different sources, such as : pebble bed swelling, thermal creep, and different thermal expansions of the structural and pebble bed materials. These stresses may damage the pebbles and endanger blanket safety, especially if heat and tritium removal deteriorate due to ceramic particle breakage.[2] However, thermal creep may reduce these stresses and compensate for the stress build-up due to the irradiation induced swelling.[3] On the other hand, thermal expansion of the pebble bed and irradiation swelling of the pebbles leads to a local increase in the contact area between particles and consequently to an increase of the heat transfer properties.[4] As the thermal expansion of the pebble beds is larger and the mechanical rigidity is smaller than the corresponding values of the structural material, the beds will be subjected to compressive stress.[5] Therefore, there is a need to determine the relation between thermal conductivity and compressive stresses.

This experimental work is intended to provide data about the effective thermal properties of beryllium-helium pebble beds. The experimental results may be used to help in the design of the blanket and provide data required for the theoretical models of the pebble beds. The experimental work was performed through three groups of experiments. The first group of experiments were dedicated to the study of the thermal conductivity of the beryllium-helium pebble bed and the Be/SiC interface heat conductance as a function of the bed mean temperature. The second group of experiments were performed to study the effective thermal conductivity of beryllium with air, vacuum, nitrogen, and helium as a cover gas to show the effect of the cover gas type. While, the third group of experiments were conducted to study the effect of the external applied pressure on the effective thermal conductivity as well as the interface heat conductance. One of the main objectives of this work is to compare the obtained results with some experimental and model data for the beryllium-helium packed bed thermal conductivity.

II. EXPERIMENTAL APPARATUS

Numerical simulations using ANSYS code, were conducted to determine the bed dimensions and the region where there is a 1D-heat transfer inside the bed under different heat loss boundary conditions. This is to make sure that the thermocouples are located in that 1D-heat transfer region inside the bed. Here the bed dimensions are larger than other test articles designed before in order to improve accuracy by decreasing the 2D-temperature profile effects. An experimental apparatus, shown in Figure 1, was constructed to conduct the required experiments. It consists mainly of the pebble bed, heater, heating block, cooling block, insulation materials, bell jar and hydraulic press.

Be pebbles were contained in a cylindrical container made of stainless steel-316 with a 60mm height, 102mm inner diameter and 108mm outer diameter. Two groups of thermocouples, uniformly distributed along the bed axial direction, were used to get identical temperature measurements. The two groups, each consisting of 6 thermocouples, were placed normal to the heat flow direction in order to minimize their effect on the bed's isotherms. The thermocouples' probes were placed 10mm from the bed centerline at two different azimuthal angles. Type J thermocouples with 1/16in sheath diameter (304 SS sheath) were used. Above the container, there is a copper heating block to uniformly transfer the heat from the heater to the beryllium pebbles. A 800-W band heater, attached to the copper block, was used to heat the bed.

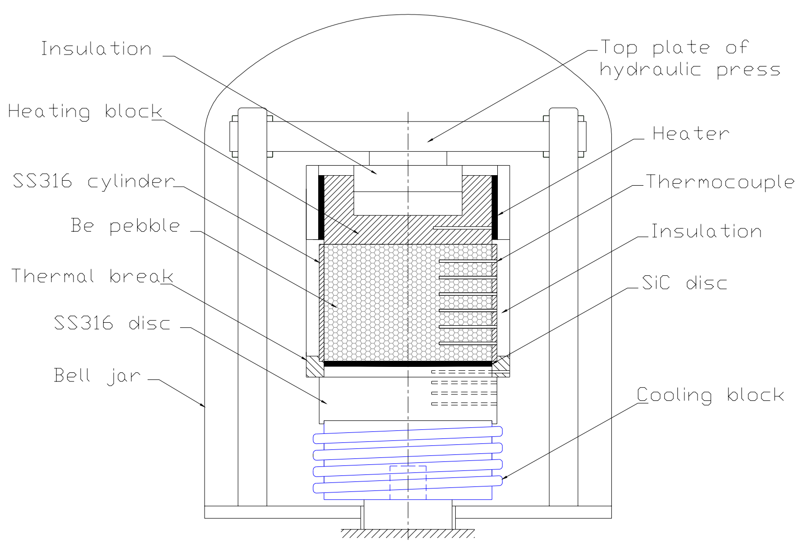

Figure 1. Schematic drawing of the experimental apparatus

At the bottom, the container is closed by a SiC disc, which is used as a clad material for the bed. Diamond machining of the SiC disc is needed for thermocouple installation to measure its temperature. The heat flux was measured by using a heat flux meter placed just below the SiC disc. The heat flux meter consists of a stainless steel-316 disc with well-known thermal conductivity and two groups of thermocouples. The thermocouples were precisely located, at regular distances, in the heat flux meter to measure the temperatures at specific points. The heat flux sensors were not used due to their low temperature capability and difficulty with bonding to the SiC surface.

The cooling block has a copper tube coil, in which the coolant is circulated, wrapped around and soldered to the block surface. Paratherm was used as a coolant instead of water because it provides the capability of running experiments at high temperatures. Close attention was paid to the insulation around the bed, heater, and heat flux meter in order to minimize heat loss and to direct heat flow vertically through the bed. The heat transmitted through the bed was determined to be about 50% of the power input to the heater. High temperature glass-mica ceramic and ceramic paper were used for insulation purposes. The bed was placed inside of a bell jar, in order to control the cover gas type and its pressure. A pressure gauge was connected to the input gas line to control its pressure. The test article was placed inside a beryllium enclosure (glove box) due to the toxicity of the beryllium dust. A hydraulic press was attached to the glove box to provide the required external pressure. The measured temperature signals were captured by a data acquisition system and stored in a personal computer.

III. EXPERIMENTAL PROCEDURE

A group of experiments were dedicated to study the effective thermal properties of a beryllium pebble bed as a function of the bed mean temperature. Helium was used as a cover gas at the atmospheric pressure and the bed mean temperature ranged from 90°C to 420°C. No external pressure was applied for these runs. Another group of experiments were conducted to study the effect of the gas type on the effective conductivity of the beryllium bed. Helium, nitrogen, air and vacuum were used as a cover gas at the atmospheric pressure and the bed mean temperature ranged from 100°C to 350°C. The third group of experiments were conducted to study the effect of external applied pressures on the bed effective thermal properties. The external pressure ranged from 0.4 to 2.0 MPa and helium with atmospheric pressure was used. The runs were conducted by heating the bed to the required temperature and then applying the external pressure and keeping this pressure constant. The external pressure was applied by using a manually driven hydraulic ram press and measured with a load cell.

Packing fraction of 60.6% was obtained for all runs with Be pebbles of 2mm diameter. The bell jar was evacuated by a mechanical pump and then filled with the cover gas. The gas composition and pressure were maintained within a vacuum bell jar. Within the range of gas velocity used in fusion applications, the runs in previous study[7] showed that there was no effect of the superficial gas velocity on the temperature profile. Therefore, the runs conducted here were in stagnant helium condition. The heat flux was adjusted, by varying the voltage input to the heater, until the steady state mean temperature of the bed was reached. It takes about a couple of hours to reach the steady state (when $\Delta T/\Delta t <$ 0.025 °C/min). Before starting any run, the heater and the vacuum pump were turned on simultaneously to heat up the bed and remove the moisture from the bell jar.

IV. RESULTS AND DISCUSSION

The measured temperature values throughout the bed show a linear temperature profile with different temperature ranges. Figure 2 shows the temperature distributions for a 2mm beryllium-helium pebble bed with a bed mean temperature ranged from 100°C to 420°C. The points of each run can be fitted well by a straight line, indicating that the effective thermal conductivity across the bed is practically constant.

Steady state temperature measurements, which define the temperature distribution in the bed, were used to calculate the effective thermal conductivity of the pebble bed using one-dimensional heat conduction equation. The bed effective thermal conductivity was calculated using equation (1), where the measured heat flux throughout the bed is divided by the temperature gradient.

$$k_{eff} = q'' \,.\, (\Delta x / \Delta T) \qquad (1)$$

Where Δx is the distance between two specific thermocouples and ΔT is the difference in their temperature's reading. The bed-clad interface thermal conductance coefficient, h, was obtained by using the following equation:

$$h = q'' / (T_e - T_c) \qquad (2)$$

Where T_e is the temperature at the bed-clad interface obtained by extrapolation of the measured temperature profile of the bed and T_c is the temperature measured at the clad, SiC, surface.

Figure 3 shows the effective thermal conductivity of a 2mm beryllium-helium pebble bed as a function of the bed mean temperature, T_m, where 90°C ≤ T_m ≤ 420°C. The experimental results agree well with SZB[6] model predictions and previous data obtained by Dalle Donne.[7] The effective thermal conductivity increases from 2.15 to 3.00 W/m.K with the increase of the bed mean temperature from 90°C to 420°C. In other words, the effective thermal conductivity increases by a factor of 1.4 with the above mentioned temperature range. With temperature increase, thermal conductivity of beryllium decreases and thermal conductivity of helium increases, the resulting effect is a small increase in the bed effective thermal conductivity. The relation between the effective thermal conductivity, k_{eff}, and the bed mean temperature, T_m, can be linearly correlated as: $k_{eff} = 0.0022\ T_m + 1.9712$

Figure 4 shows the interface thermal conductance coefficient as a function of the bed mean temperature range, 100°C ≤ T_m ≤ 420°C. The interface conductance increases with an increase in the bed mean temperature. More specifically, it increases by a factor of 1.93 with an increase in the mean temperature from 100°C to 420°C. It behaves in a similar manner to the bed effective thermal conductivity.

The experimental results shown in Figure 5 reveal the effect of the gas environment on the effective thermal conductivity, where air, vacuum, nitrogen, and helium were used as a cover gas. It is clear that using helium as a cover gas with beryllium gives the highest thermal conductivity (range from 2.23 to 2.75W/m.K) while the smallest conductivity (range from 0.35 to 0.38 W/m.K) was obtained with vacuum at the same temperatures. The Be-He data show an increase in the conductivity values with a temperature increase. Be-N_2 data Be-air data show similar increases but the rate of increase is smaller than that of Be-He. The thermal conductivity values obtained with air and nitrogen are close and smaller than those of helium by a factor of ~2.70. For the different values of the bed mean temperature, the thermal conductivity values obtained in the vacuum environment were the smallest and nearly constant. Although the thermal conductivity of the gas is smaller than that of the pebbles, the gas contribution has a larger effect on the effective thermal conductivity of the bed, increasing the effective thermal conductivity by a factor of ~ 6 when compared with vacuum. This seems reasonable, since the gaseous area through which the heat is transferred is larger than the contact area between pebbles. Due to the small contact area between pebbles, the heat flow throughout the cover gas represents a larger percentage of the total heat transferred throughout the bed.

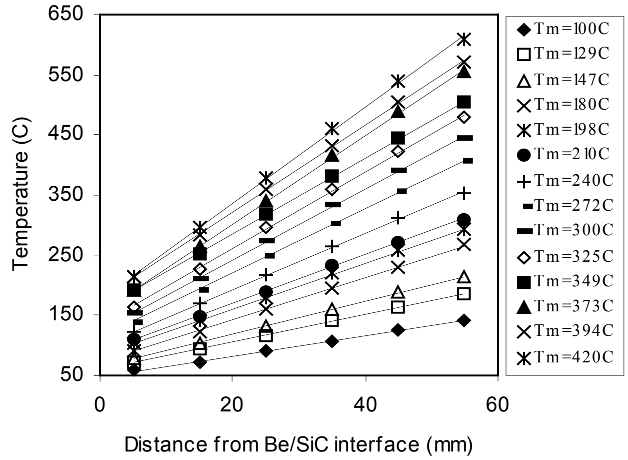

Figure 2. Axial temperature distributions of Be-He bed

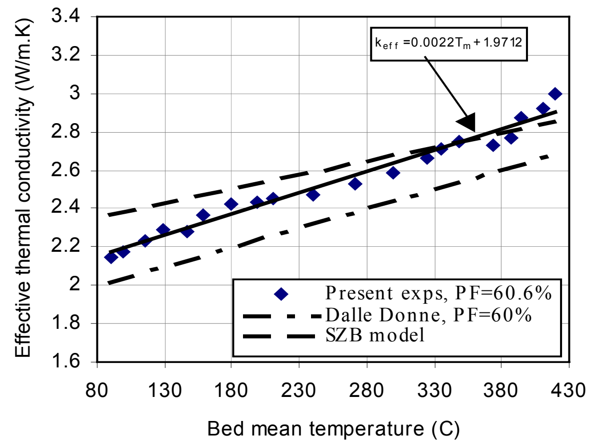

Figure 3. Bed effective thermal conductivity as a function of the bed mean temperature

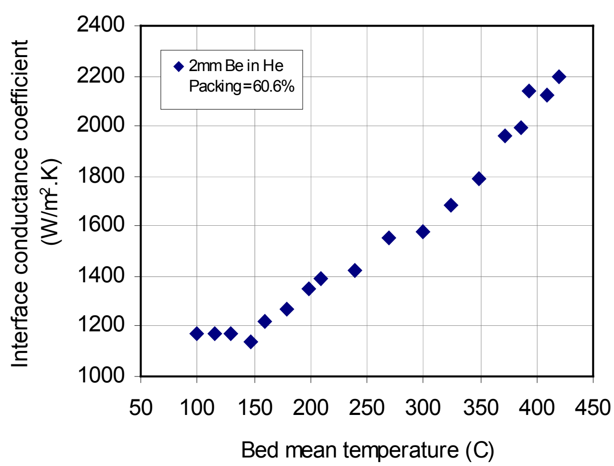

Figure 4. Interface conductance coefficient as a function of the bed mean temperature

The effective thermal conductivity of a beryllium-helium pebble bed as a function of an external applied load, in the range of 0.4 to 2.0 MPa, was measured. For this range of external pressure, the results are shown in Figure 6 for four bed mean temperatures (100°C, 180°C, 270°C, and 350°C). The values of the conductivity are directly proportional to the applied pressures. When applying an external pressure of 2 MPa, with these four temperatures, the effective thermal conductivity increased by factors of 2.53, 2.30, 2.18, and 2.11 respectively, relative to that with no load. It is noted that the increase of the effective conductivity decreases with increasing temperature. Dalle Donne[7] data (correlation) gives a similar trend to the results obtained here while, Tehranian[8] data has lower values.

With pressure increasing, the behavior of the bed show the following three changes. First, the pebbles are rearranged into denser packing, increasing the packing fraction, which increases the effective conductivity. Second, the contact area between pebbles is increased, leading to an increase in the conductivity. Third, increasing elastic and/or plastic deformation is another reason for increasing the conductivity with increasing pressure. Compression of the pebble bed affects greatly its effective conductivity. This is true, for beryllium, because of the larger ratio of thermal conductivity of beryllium to the cover gas.[5] For fusion blankets, the effect of deformation on the thermal conductivity may be neglected for ceramic breeder materials, but it is significant for beryllium pebble beds[3].

Figure 7 shows the behavior of the bed conductivity when the applied pressure is increased from 0.3 to 2.16 MPa and then decreased to 0.3 MPa again. As expected the conductivity increased with the pressure increase. However, with pressure decrease the conductivity decreased, but its values were higher than the corresponding values at the same pressure during the pressure increase by about 0.5 W/m.k between 1 and 1.5 MPa. When the pressure moved to zero, the bed conductivity remained higher than its initial value by about 0.3 W/m.K. It is clear that there is a hysteresis effect associated with the conductivity behavior with the loading and unloading of external pressures. During the pressure decrease, the pebbles can not return to their initial packing state, which leads the bed to keep its conductivity higher than the original value. Figure 8 shows the effect of the external applied pressure on the beryllium-SiC interface conductance coefficient. The increase in the interface conductance values with pressure shows variations similar to those of the thermal conductivity. As the applied pressure increased to 2 MPa, the interface conductance coefficient increased by a factor

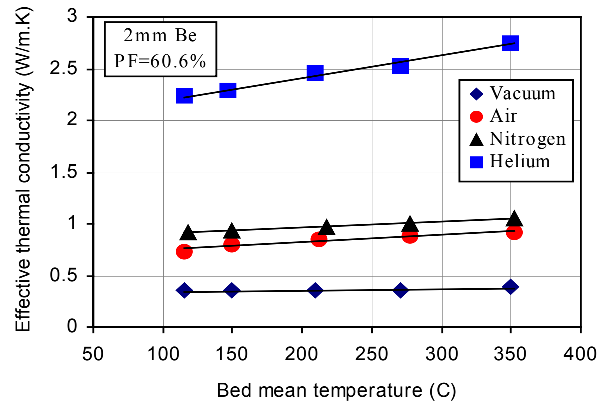

Figure 5. Effective thermal conductivity of beryllium bed with different cover gases

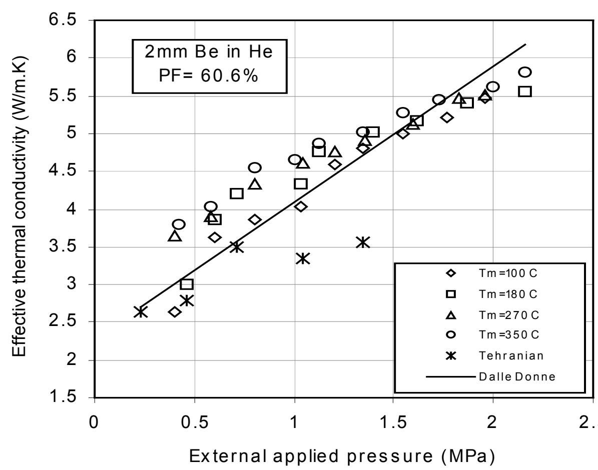

Figure 6. Effect of external applied pressure on beryllium bed effective thermal conductivity

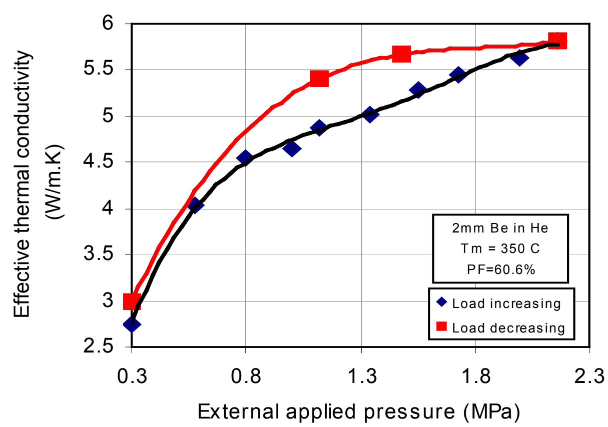

Figure 7. Bed effective thermal conductivity with load increasing and decreasing

of 2.5 relative to that with zero pressure, for bed mean temperature, T_m= 270°C.

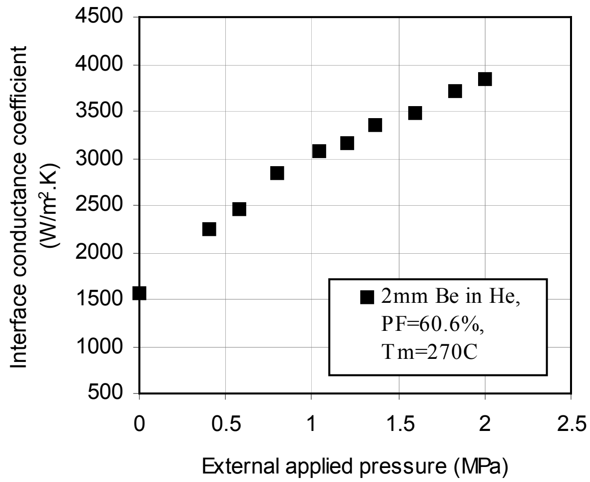

Figure 8. Effect of external applied pressure on Be-SiC interface conductance coefficient

V. CONCLUSIONS

The effective thermal properties of beryllium pebble beds were experimentally studied. These thermal properties serve as a database for blanket design and theoretical models of the pebble beds. The effective thermal conductivity as well as the Be-SiC interface thermal conductance coefficient increase with the increase of temperature and external applied pressure. The results of this work agree reasonably well with previous experimental data and model predictions. Similar to the effect of the applied pressure, one can expect that effective thermal conductivity would increase during the blanket operation due to irradiation swelling and/or differential expansions. Interpretation of the applied pressure to operational parameters, such as amount of swelling and differential thermal stresses is somehow challenged and will be quantified in the near future.

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