EXPERIMENTAL STUDY OF THE EFFECTIVE THERMAL CONDUCTIVITY OF A PACKED BED AS A TEMPERATURE CONTROL MECHANISM FOR ITER CERAMIC BREEDER BLANKET DESIGNS *

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Introduction

For an ITER ceramic breeding blanket, the breeder temperature must be kept above about 400°C for adequate tritium release. At the same time, low coolant temperatures are desired to maximize reliability. A novel and practical concept was proposed for the thermal resistance gap between the coolant and solid breeder to allow their operating temperatures to be optimized for ITER.[1] This thermal resistance gap is to be filled with a mixture of beryllium pebbles and helium gas. Since the tritium breeding ratio is strongly dependent on the amount of beryllium, a high packing fraction of the bed (~80%) is desired to increase the tritium production in the blanket.

The proposed concept also provides operational flexibility to accommodate ITER power variation through control of the thermal conductance of the gap. This control mechanism provides the capability to maintain the breeder within the operating limits defined by the minimum temperature for tritium release and the maximum temperature, which is usually based on sintering. Sintering also retards tritium release, thereby increasing the blanket tritium inventory.

Several experiments have been performed in the past to determine the thermal conductivity of a packed bed. Most of these experiments were done for beds containing a single particle size (which provide about 60–65% packing fraction).[2] Experimental data at lower porosities are available primarily from fission-related experiments using UO_2 particles, which have a thermal conductivity 30 times lower than that of Be.[3] The thermal conductivity of a metallic packed bed is strongly dependent on both the porosity and conductivity ratio, and therefore data were lacking to validate models under development [4] and to provide direct empirical measurements for use in the design of the ITER breeding blanket.

This paper summarizes new experimental studies of the effective thermal conductivity of a metallic packed bed. The experiments were conducted for both single-size and binary particle distributions under different gas pressures. Aluminum and copper were chosen to simulate the physical properties of beryllium, which is the material proposed for reactor applications. Helium was used as the primary gas component, while neon and nitrogen were also used for the investigation of cases with extremely high particle-to-gas thermal conductivity ratios. The pressure control of the effective thermal conductivity of the stagnant packed bed is obtained through the Smolukovski effect, and is affected by the size of the particles and the nature of the particle contact.

2. Bed and Material Characterization

2.1 Material Selection and Analysis

The most important property of the bed is the ratio of conductivities of the solid and gas phases. Aluminum has a thermal conductivity close to that of beryllium, and was therefore chosen as the primary simulant. Beryllium was avoided due to safety, availability, and cost concerns. Copper was chosen to provide an alternate high conductivity solid material. Neon and nitrogen were used as alternate low thermal conductivity gases. With this set of materials, a good range of conductivities and conductivity ratios could be tested to validate the models and cross-check the Al+He measurements.

To obtain high packing fraction, the ratio of particles sizes must exceed 8~10. This allows the smaller size to fill the gaps between the larger balls. Larger size ratios are probably acceptable, but can lead to either very large or very small sizes. With ternary beds, the optimum ratio of largest to smallest size has been determined to be ~40 [5]. An additional concern is to maintain prototypical values of δ_g/d_p, where δ_g is the gap width and d_p is the particle diameter. To meet these criteria, Al microspheres with the following sizes were studied:

gas-atomized powder	75–150 µm
centrifugally-atomized shot	0.4–0.7 mm
granular shot	0.7–0.8 mm
ball bearings	4.3 mm

Another important concern in chosing materials is to properly simulate the surface characteristics of the particles, since they play such a large role in heat transfer with metallic beds. In this regard, it is difficult to specify a single value of surface roughness or a specific shape because it not known precisely what the reactor material will be like. For these experiments, several types of aluminum were examined, ranging from very coarse granular shot to very smooth ball bearings. This allowed us the ability to test a range of roughnesses and shape factors.

Oxide layers appearing on metallic surfaces can alter heat transfer in the important contact region. BeO has a very high conductivity, such that its oxide would be expected to have little effect. A possible exception would occur if the oxide introduced additional roughness to an otherwise smooth material form. While aluminum oxides have significantly reduced conductivity compared to pure Al, the depth of oxide formation in Al is known to be extremely low — less than a few microns. A thin oxide layer is highly protective in Al, preventing further oxidation. In spectroscopic examinations of the aluminum particles used in the experiments, the oxide layer thickness was undetectable. The absence of a significant oxide layer would be expected to provide a good simulation of Be. In contrast, copper continues to oxidize as a function of time.

2.2 Packing Experiments

The aim of the packing experiments was to develop a packing method which provided the highest and most uniform packing of the particle beds. The method developed was then applied to the heat transfer test section where visual observation of the packing arrangement is not possible. To achieve this goal, a plexiglas annular test section was constructed. This test section was bolted to a vibrator, with two feeder tubes attached at the top of the test section to introduce the particles into the annular bed region during vibration. It was found experimentally that the most uniform packing is obtained by filling the test section while it is vibrating. The present study also confirms that for single size particle beds, the packing arrangements are predominantly orthorhombic. The packing fraction for single-size particle beds was in the range 60~64%. (The packing fraction is defined as the ratio of the volume occupied by the particles to the total volume of the bed.) The powder bed had the lowest packing fraction, due to agglomeration effects.

A sphere-pac bed composed of particles of two sizes is termed a binary mixture. The coarse fraction consists of large particles and is surrounded by small particles and the fill gas. When packing binary mixtures, the experimental technique which provided the highest packing consisted of packing the coarse component by itself until it attained its maximum packing fraction, and then allowing the fine component to diffuse through the interstices. The same conclusion was obtained by McGeary [5]. The coarse component must also be restrained in some fashion to prevent segregation.

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2.3 Porosity Measurements

Porosity measurements were performed to examine the uniformity of the bed in the axial and circumferential directions, and to determine the radial porosity variation. These measurements were taken using a sodium-iodide detector with a ^{137}Cs γ-source. The source beam was collimated to 1/32-inch diameter. The amount of γ-ray attenuation by the particles is proportional to the local particle packing density. The results indicate that the bed obtained under the current packing method is uniform and reproducible.

Figures 1 and 2 show the experimental results for attenuation in a single-size and a binary bed, respectively. The single-size bed was filled with the 4.3-mm ball bearings, and the binary bed was a mixture of ball bearings and 0.5-mm atomized spheres. The presence of the walls disturbs the local packing and increases the voidage there. The wall effect is less important for the binary bed, where it is confined to a thin region beyond the resolution of the γ-ray beam. The porosity distribution normally follows a decaying oscillating form that settles down to a mean value in around 4 particle diameters.[5] Our data show similar behavior; the oscillation for the single-size ball bearings decreases towards the center of the bed, with a period of one particle diameter. In the binary bed, the presence of the smaller particles increases the magnitude and uniformity of the packing fraction. The oscillations are smaller, but still noticeable, in this case.

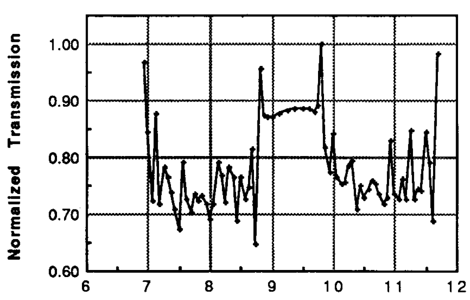

Figure 1. Porosity profile for a single-size bed

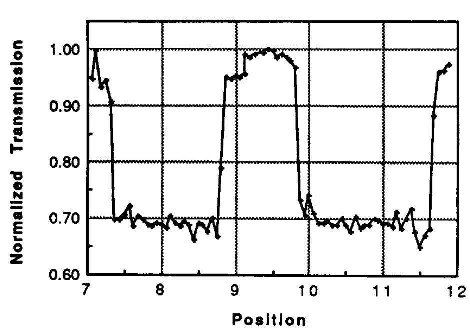

Figure 2. Porosity profile for a binary bed

3. Heat Transfer Experimental Apparatus

Figure 3 shows a schematic diagram of the test section used to acquire the data. The active test section has an outside diameter of 12 cm and a height of 24 cm, with a bed width of 4.76 cm. The test section is made primarily of copper and brass, with bakelite thermal insulation to minimize heat loss from the ends. A cartridge heater is located at the center of the test section. The centrally-heated designwas chosen primarily because the heat source could be measured more accurately, and also because it more closely represents the reactor design. The outer double cylinder was used as a water jacket. Solid particles were packed in the annular bed region between the heater section and the cooling section. The temperatures were measured along the surfaces of the inner and outer clad by Type J thermocouples

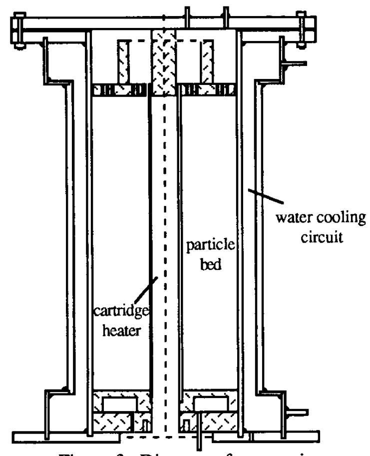

Figure 3. Diagram of test section

placed into the walls. In addition to the surface temperature measurements, the temperature profiles across the bed at the mid-plane of the test section were also recorded.

The experimental procedure starts by packing the particles with vibration energy, sealing the bed and introducing the working gas (helium or nitrogen) into the bed after evacuation. The heater and the coolant were then turned on to set up a temperature gradient in the packed bed. After confirming thermal equilibrium in the bed, the temperatures, gas pressure, and power into the bed were recorded.

4. Results

4.1 Characterization of Uncertainties

The experimental value of the effective thermal conductivity of a uniform, axisymmetric packed bed under steady-state conditions is calculated from the measurement of several parameters, using the following equation:

$$k_{eff} = \frac{V \cdot I \log(r_o/r_i)}{2\pi L \Delta T} \quad (1)$$

where
$V \cdot I$ = power to the heater
r_o, r_i = inner and outer radii of the bed
L = heated length
ΔT = temperature difference across the bed.

The experimental accuracy of measuring the effective thermal conductivity of a packed bed depends partly on the accuracy with which the relevant temperature difference, the input power, and the geometrical dimensions can be determined. This error can be estimated using the following equation:

$$\frac{\sigma_k}{k} = \sqrt{U_I^2 + U_V^2 + U_{ro}^2 + U_{ri}^2 + U_L^2 + U_{Ti}^2 + U_{To}^2} \quad (2)$$

where $U_i = \frac{\sigma_i}{k_{eff}} \frac{\partial k_{eff}}{\partial x_i}$ represents the error introduced from the various terms in eqn. (1).

Additional uncertainties arise due to end losses and/or asymmetries. In order to estimate these errors, the TOPAZ heat conduction computer code [6] was used to model the experimental apparatus. The results indicated that for the machining tolerances obtained in the test section, temperature errors due to asymmetry should be <1%. Depending on the bed and insulator thermal conductivities, the percentage of heat losses through the ends was estimated to be between 5 to 15% for the present experiments.

However, the actual errors in the measured temperature profiles and heat fluxes near the mid-plane are much less than the global errors in the heat flux. This is due to the fact that the heater is designed to provide constant heat flux through the entire length, and consequently, due to symmetry, the radial heat flux near the mid-plane is only slightly affected by axial end losses. To determine the actual heat flux at the surfaces of the bed, heat flux sensors were attached at the mid-plane on the inner and outer surfaces of the bed. For example, local heat flux measurements were made using a stagnant pure helium bed. (The observed errors would then be conservative, since the axial heat losses decrease as the bed conductivity increases.) Comparing the local surface heat flux with the total power divided by the surface area, the maximum difference between calculations and measurements was 0.8% for the inner surface heat flux and 4.0% for the outer surface heat flux.

In an annular packed bed with heat flow purely radial and constant bed thermal conductivity, the theoretical temperature distributions should be straight lines on semilogarithmic coordinates. Fig. 4 contains an example plot of the radial temperature variation with 4.3 mm Al and He at 1 atm. The figure shows that the experimental points are correlated quite well by a straight line in such a diagram. It should be noted that a slight temperature difference occurs between the measurement at the inner wall and the extrapolated temperature from the bed to the wall. This occurs because the presence of the walls disturbs the local packing, resulting in higher local porosity and additional resistances to heat transfer. The temperature jump at the inner and outer walls of the bed can be determined using a linear regression fit from the temperature measurements across the bed.

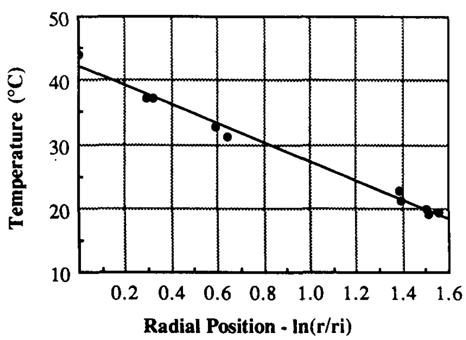

Figure 4. Typical radial temperature distribution, including temperature jump at the wall (4.3 mm Al + 1 atm He)

Based on all these arguments and the temperature measurements along the bed, it is concluded that the calculated heat flux based on the input power has about 1% error in the mid-plane and several percent error at the edge of the active test section. Table 1 summarizes the experimental errors for mid-plane measurements.

4.2 Experimental Data

Experimental results are shown in Figure 5 for the effective thermal conductivity of single-size Al/He beds as a function of gas pressure in the range $0.01<p<0.3$MPa. Table 2 shows the measured average packing fraction for the various beds. For helium fill gas, the experimental value of effective thermal conductivity increases substantially as the gas pressure is increased. The largest effect of the gas pressure on k_{eff} is found in the powder bed. This is because when the

Table 1. Estimate of measurement uncertainties in the data

Test Description	Range of k_{eff} (W/m-K)	Range of uncertainty in k_{eff} (W/m-K)
Al powder	0.44 – 1.44	0.012 – 0.066 (2.7-4.6%)
Medium-size Al	1.14 – 2.04	0.031 – 0.068 (2.7-3.3%)
Al Ball bearings	1.41 – 2.50	0.036 – 0.087 (2.5-3.5%)

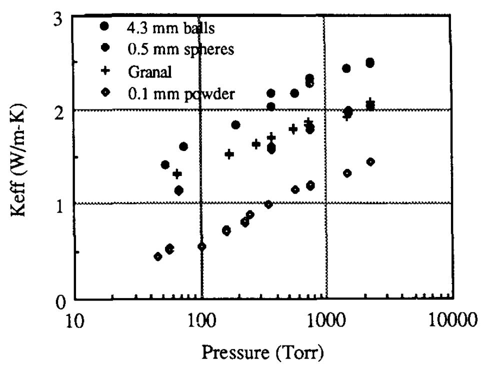

Figure 5. Pressure dependence of k_{eff} for Al/He single-size beds

Table 2. Measured Average Packing Fraction for the Different Beds

Bed Description	Packing Fraction (%)
0.1-mm powder	57.4
0.5-mm spheres	60.3
4.3-mm ball bearings	64.2
0.7-mm granular shot	61.6

separation distance between the particles becomes small, heat conduction through the fill gas is more strongly affected by the Knudsen domain. The results indicate that substantial control of k_{eff} can be achieved through pressure variation. For example, increasing the pressure from 0.2 to 2 atm increases k_{eff} by 94% for the powder bed, and 40% for the large ball bearing (4.2 mm diameter) bed.

Figure 6 compares the pressure dependence of k_{eff} in the Al powder bed for He and N_2 fill gas. There is clearly a large difference between the two cases. The absolute value of the effective conductivity is much lower in N_2, and the variation with pressure is almost unmeasurable. This reduced pressure dependence is caused by the larger ratio of conductivities between the metal and gas phases (~1200 for He vs. ~8000 for N_2).

Figure 7 shows the measured effective thermal conductivity for two binary packed beds as a function of pressure. The packing fraction for both binary beds was approximately 83%, with 63% coming from the coarse fraction and 20% from the fine fraction. Comparing single-size vs. binary mixtures at the same pressure, the effective thermal conductivity increases from 1.8 W/m-K to 6.4 W/m-K when the packing fraction increases from 62% to 83%. The effective thermal conductivity increases by 60% with a pressure increase from 0.2 to 2 atm, and a factor of 2 with a pressure increase from 0.1 to 4 atm.

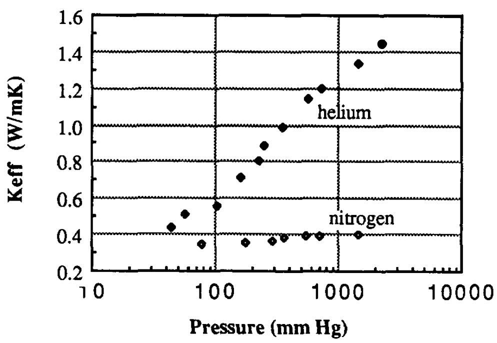

Figure 6. Comparison of pressure dependence of k_{eff} in He and N_2

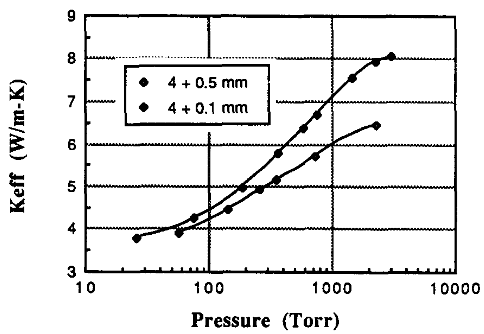

Figure 7. Pressure dependence of k_{eff} for Al/He binary beds

Conclusions

The ability to control the thermal conductivity of a metal/gas particle bed by varying the gas pressure and composition has been clearly demonstrated under a range of conditions in several single-size and binary packed beds. Variations in the conductivity of up to a factor of 4 have been observed under conditions which are practical for application to fusion reactor blankets.

Based on the experimental data, the use of He together with a binary mixture of Be appears very attractive for blanket application at this time. It results in high packing fraction, relatively high k_{eff} and significant k_{eff} controllability through pressure variation. It was observed that the pressure dependence of the effective conductivity remained strong for both very smooth and very coarse materials.

An additional control mechanism can be obtained by varying the composition of the gas. While very high conductivity ratios, such as might be obtained with Be and either Ne or N_2, appear to provide much less control by adjusting the gas pressure, they still offer the possibility of control by varying the gas composition.

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