THERMAL RESISTANCE GAPS FOR SOLID BREEDER BLANKETS USING PACKED BEDS

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ABSTRACT

The main design features of a new concept for solid breeder blanket thermal resistance gaps are described and analysis is shown for the blanket thermal characteristics. The effective thermal conductivity of a helium-beryllium packed bed configuration is studied, including the effect of a purge stream. Possible applications of this concept to ITER blanket designs are stressed.

INTRODUCTION

Control of the temperature of the breeder and coolant is important in solid breeder (SB) blanket designs, particularly for an experimental fusion reactor such as ITER. Keeping the coolant at moderate pressure and temperature enhances safety and reliability, while operating the breeder at higher temperatures is necessary to ensure adequate tritium release. The required thermal resistance between the solid breeder and coolant could be provided by means of a thin gap filled with an inert stagnant gas, such as He or Ar or a mixture of these. However, this type of thin resistance gap, where small changes in the gap could substantially affect the solid breeder temperature, is not considered very attractive, particularly in designs with long rods or slabs where maintenance of the gap thickness under fusion conditions could be difficult.

A novel and practical concept is proposed for this type of gap which can be applied to water- or helium-cooled solid breeder designs, or even liquid LiPb designs. This concept is based on the utilization of a dispersion of gas and solid particles, which offers unique characteristics of heat and mass transfer and fluid mechanics [1]. Using a packed bed of beryllium particles and helium in the gap has several advantages, including:

1) The bed characteristics (gap thickness, porosity, type and size of particles, type and pressure of gas) can be tailored to ensure the desirable thermal resistance of the gap;
2) The increased gap size, as compared to gaps with pure He, allows for better uniformity and predictability of the thermal resistance;
3) The use of beryllium in a near-homogeneous mixture enhances the tritium breeding capabilities of the design;
4) Improved control over the solid breeder temperature (through both passive and active means) permits operation over a wider range of power densities and transient conditions without violating temperature constraints;
5) Be swelling can be partially accommodated by expansion into the bed void fraction;
6) In general, changes in the solid particle properties only weakly affect the thermal conductivity of the mixture, which is more strongly controlled by the gaseous component;
7) An additional barrier is provided against tritium permeation from the solid breeder to the coolant;
8) Tritium generated in the beryllium multiplier is more easily removed, perhaps as a part of the basic solid breeder purge system.

The proposed gap configuration is first described, including the required gap thickness as a function of the He/Be volume fractions. Next, the mathematical model for the effective thermal conductivity is presented. Several blanket parameters influence the effective thermal conductivity. One of these – the effect of a flowing purge stream – is described in detail.

GAP CONFIGURATION

The proposed gap configuration is applicable to any blanket where an appreciable temperature drop between the breeder and coolant is required. For the purpose of this paper, the helium-cooled solid breeder blanket for ITER of Ref [2] is chosen for the gap conductance calculations. This blanket consists of several canisters poloidally positioned side by side on the outboard region. Each canister contains an array of rods in which the solid breeder and Be multiplier are located.

Initially a two-zone and a three-zone configuration for each rod were considered, as shown in Fig. 1. The two-zone configuration consists of a solid breeder rod surrounded by an annulus of Be in sphere-pac form whereas the three-zone configuration also includes an extra solid Be annulus.

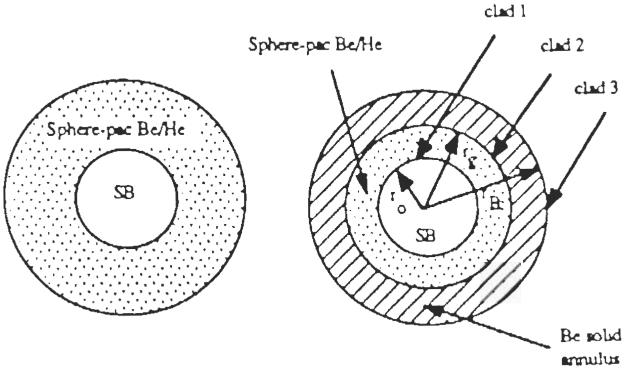

Figure 1. Rod configurations which provide the required temperature drop between the solid breeder and coolant

The formulas for the temperature calculations are derived using principles of the effective thermal conductivity and superposition of heat flows, as described in the following section. The principle of superposition means that the temperature field can be formed as a sum of the independent effects of internal and external heat sources. The formulas used for "3-zone" rods are shown below. For the two-zone rods, terms connected with the solid annulus are omitted. In all cases, the internal heat generation in the thin clads (0.5mm) and the temperature drops across the clads are relatively small and can be omitted. The contact resistance between the solid breeder and clad was estimated as being small compared to the solid breeder thermal resistance based on data for UO_2 [3] and was thus neglected in the calculations.

$$\Delta T_{SB} = \frac{q'''_{SB} r_o^2}{4 k_{SB}} \tag{1}$$

$$\Delta T_g = \frac{q'''_{SB} r_o^2}{2 k_{ef}} \ln \frac{r_g}{r_o} + \frac{q'''_g r_o^2}{4 k_{ef}} \left(\frac{r_g^2}{r_o^2} - 2 \ln \frac{r_g}{r_o} - 1 \right) \tag{2}$$

$$\Delta T_{Be} = \frac{(q'''_{SB} + q'''_g)}{2 k_{Be}} r_g^2 \ln \frac{r_{Be}}{r_g} + \frac{q'''_{Be} r_g^2}{4 k_{Be}} \left(\frac{r_{Be}^2}{r_g^2} - 2 \ln \frac{r_{Be}}{r_g} - 1 \right) \tag{3}$$

$$\Delta T_f = \frac{q'''_{SB} r_o^2 q'''_g + (r_g^2 - r_o^2) + q'''_{Be} (r_{Be}^2 - r_g^2)}{2 r_{Be} 2 h_{He}} \tag{4}$$

where ΔT_{SB}, ΔT_g, ΔT_{Be} and ΔT_f are the solid breeder, gap, Be and film temperature drops; q'''_{SB}, q'''_g and q'''_{Be} are the heat generation per unit volume of the solid breeder gap and Be regions; r_o, r_g and r_{Be} are defined in Fig. 1; k_{SB}, k_{ef} and k_{Be} are the thermal conductivities of the solid breeder, gap and Be regions; and h_{He} is the heat transfer coefficient for the helium flow over the rod. For the calculations q'''_{SB}, q'''_g and q'''_{Be} were assumed to be the same ($10 MW/m^3$) and the thermal conductivities were assumed constant based on a mean temperature in each zone.

As a comparison of the two configurations, Fig. 2 shows the combination of solid Be annulus thickness and He/Be gap thickness required to produce a total temperature drop of 350°C for different He/Be volume fractions in the gap. THe effective conductivity was estimated using correlations from [1,7]. Lines of constant rod diameter are also included. The graph shows that for a rod diameter of about 40mm, which is desirable for the ITER blanket design of Ref. [2], a gap is required for both configurations. Using only a 30/70 He/Be sphere-pac gap ("2-zone" rod, $\delta_{Be}=0$) requires a gap thickness $\delta_g \sim 14-15$mm and a 40-mm rod diameter. This configuration is attractive as it includes all the advantages listed in the introduction and since the neutronics results show that the tritium breeding ratio for the 30/70 He/Be sphere-pac case is acceptable [2].

MODEL FOR THE EFFECTIVE THERMAL CONDUCTIVITY

The gap is a heterogeneous gas-solid system through which heat propagates by conduction (through solid particles and gas), convection and thermal radiation. Because of the difficulty in defining the exact geometry for interphase interactions and the complexity of processes, the heat transfer through the gap is considered as an effective conduction process.

The effective thermal conductivity, k_{ef}, is a characteristic of the mix of macro-dispersed solid and gas which combines both their physical and geometrical properties. Under steady state conditions, k_{ef} is a function of several parameters, as shown by the following equation:

$$k_{ef}/k_{gas} = f\left(\frac{k_s}{k_{gas}}, \frac{k_{tr}}{k_{gas}}, \frac{k_{nr}}{k_{gas}}, \frac{k_p}{k_{gas}}, \varepsilon, \frac{\delta_g}{d_p}, \phi, f_p \ldots \right) \tag{5}$$

where k_{gas} and k_s are the thermal conductivities of the gas and solid; k_{tr}, k_{nr} and k_p account for the effects of thermal and neutron radiations and low pressure; ε is the mean porosity; δ_g is the gap thickness; d_p is the mean diameter of particles; ϕ and f_p are the form factor and polydispersion factor, which account for the distribution of particle sizes.

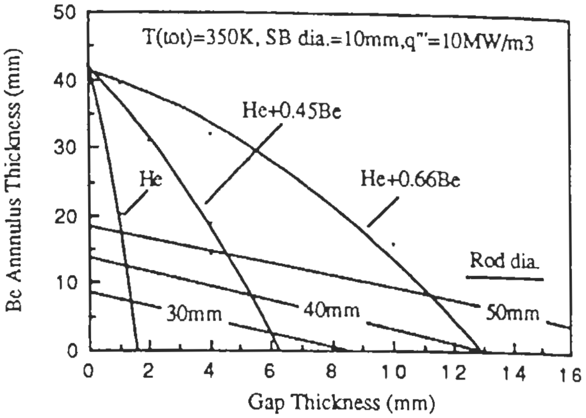

Figure 2. Gap and annulus thicknesses required to maintain a temperature drop of 350°

In spite of the existence of several formulations and approaches, Equation (5) cannot be predicted with desirable accuracy even if k_{nr}/k_{gas} is omitted. Very complicated thermal processes bring an approximate character to theoretical models and to the correlation and extrapolation of experimental data. Among the analytical models, the formula given by Kunii and Smith [5], is most popular [6,7]. But predictions based on this approach have only limited accuracy especially when δ_{gap}/d_p is small (<10). For example, Fig. 3 shows a comparison of the calculated k_{ef}/k_{gas} for a Be/He mix based on different correlations for the following conditions: ε=0.4; T=275°C; $P=10^5$Pa; δ_{gap}/d_p>10. The difference can be more than a factor of 2, for example, between the expressions from Kunii and Smith [5] and Wakao and Vortmeyer [8] for both He and Ar.

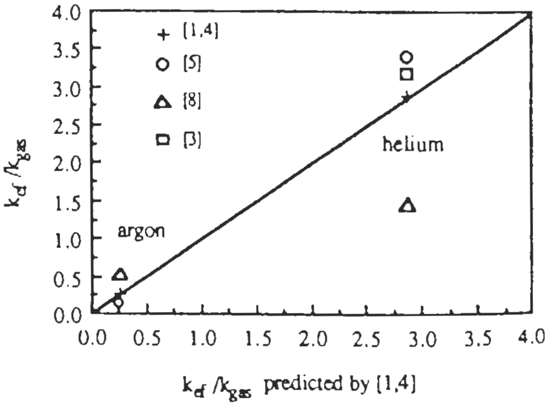

Figure 3. Comparison of k_{ef}/k_{gas} based on different correlations.

For the calculations in this paper, experimental data were used from [1 and 4] for a bed with graphite particles and from [6] for various materials.

DEPENDENCE OF THE EFFECTIVE THERMAL CONDUCTIVITY ON THE BLANKET CONDITIONS

For the solid breeder ITER blanket considered here, equation (5) can be simplified because of the weak dependence on some parameters. For example, the temperature of the gap is less than 700°C and, thus, the effect of thermal radiation (k_{tr} in equation (5)) is minimized. Similarly, the dependence on pressure (k_p) and wall effect (δ_g/d_p) can be minimized for high helium pressure inside the gap and large d_p, and for δ_g/d_p about 10. Note that for small particles and bed porosity, the local Knudsen numbers can be large and pressure variation can be used as a means of controlling the bed effective thermal conductivity.

Effect of Oxide Layers

Formation of an oxide layer on the Be spheres would affect k_s, and in turn k_{ef}, through equation (5). The thermal conductivity of the solid spheres can be expressed as a combination of the thermal conductivity of Be and BeO (k_{Be} and k_{ox}) [9].

$$k_s = k_{Be}\left(1 + \frac{\delta_{ox}\, k_{Be}}{d_p\, k_{ox}}\right)^{-1} \tag{6}$$

where δ_{ox} is the thickness of the oxide layer.

Table 1 shows the effective thermal conductivity for a Be/He gap as a function of the assumed oxide layer thickness for ε=0.3 and ε=0.4. Because of the relatively high thermal conductivity of BeO, the effect of the oxide layer is quite small. By comparison, the effect on a metal whose oxide has a low conductivity (such as Al) can be quite large.

Table 1. Illustration of the influence of oxide-layer thickness on k_{ef}

d_{ox}/d_p	k_s/k_{gas}		k_{ef}/k_{gas}[6]			
			Be		Al	
	Be	Al	ε=0.4	ε=0.3	ε=0.4	ε=0.3
0	691	1000	14.3	24	14.5	26
0.01	677	636	14	23.5	10	23
0.05	625	262	13.3	22.5	9.2	18
0.1	571	151	12.6	22	8.2	17
0.15	525	104	12	21	7.8	15

The following thermal conductvities were used based on a relative temperature of 21°C.

k_{ox} = 4 W/m-K for Al_2O_3
k_{ox} = 76 W/m-K for BeO
k_s = 232 W/m-K for Al
k_s = 159 W/m-K for Be

Purge Flow through the Gap

Conceivably, the same purge could be used for both the solid breeder rod and the annular Be/He gap. The use of a helium purge through the rods is required for tritium removal in the blanket. It could also potentially be used to control the effective gap thermal condutivity and for partial heat removal during loss-of-coolant accidents (LOCA) and/or shutdown conditions. The distribution of the average purge velocity between the solid breeder and the gap, u_{SB} and u_g, is based on the ratio of tritium removal from the solid breeder and gap, $Q_{T(SB)}/Q_{T(g)}$

$$\frac{u_{SB}}{u_g} = \frac{Q_{T(SB)}}{Q_{T(g)}}\,\frac{A_g}{A_{SB}} \tag{7}$$

where A_g/A_{SB} = ratio of flow area of gap and solid breeder regions. "u" is the "superficial velocity" based on the total flow rate and full channel cross sectional area. Since $A_g > A_{SB}$ and $Q_{T(g)} << Q_{T(SB)}$, u_{SB} will be much larger than u_g ($u_{SB}/u_g \sim 10$).

The effective thermal conductivity of the gap with flowing helium, k^*_{ef} is given by [6,7].

$$k^*_{ef}/k_{gas} = \frac{k_{ef}}{k_{gas}} + B\,Pr\,Re_p \tag{8}$$

where

$$\text{if } \frac{D}{d_p} > 25 \qquad B = 0.11$$
$$\text{if } \frac{D}{d_p} > 5 \qquad B = \frac{0.09}{1+10\left(\frac{d_p}{D}\right)^2} \tag{9}$$

where D is the hydraulic diameter, Pr is the Prandtl number and Re_p is the Reynolds number based on the particle diameter.

$$Re_p = \frac{\rho u d_p}{\mu} \tag{10}$$

Both the gap region as well as the solid breeder are assumed to be in sphere-pac form. Fig. 4 shows the effective thermal conductivity for the solid breeder and Be regions as a function of the purge velocity. The influence of the purge on k_{ef} of the Be region is small if u_g is less than about 0.1 m/s. In this case, Re_p is small and the velocity-dependent term in Eq. (8) is much smaller than the static conductivity. Since u_{SB} is higher than u_g by about an order of magnitude, based on equation (7), and because the static solid breeder conductivity is so much lower, the effect of the purge on k_{ef} in the SB region is much more pronounced. It is also important to note here that, according to experimental data, k_{ef} may show a stronger dependence on velocity in the regime 0<Re<1~2 [5,7].

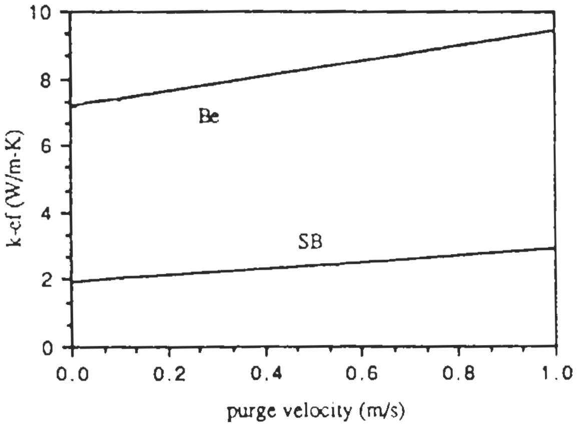

Figure 4. Dependence of the effective thermal conductivity on purge flow velocity for the gap and solid breeder.

In order to determine whether the purge can significantly help in removing the afterheat after shutdown or in the event of a LOCA, the energy removed by the purge and the pressure drop were calculated as a function of the purge velocity. The maximum possible temperature of the purge at the exit of the solid breeder section, $T_{He(ex)}$, is equal to the average SB temperature.

$$T_{He(ex)} = T_{SB(Max)} - \frac{q'''_{SB}\, r_0^2}{8\, k_{SB}} \tag{11}$$

where $T_{SB\,(max)}$ is the maximum SB temperature at the rod center.

Similarly the maximum possible temperature of the purge at the exit of the Be/He gap section is:

$$T_{He(ex)} = T_{g(Max)} - q_g''' \frac{(r_g^2 - r_0^2)}{8\, k_{ef}} \tag{12}$$

The power removed by the purge, P_p, for a given purge inlet temperature, $T_{He(in)}$, is given by:

$$P_p = c_p[\rho_{f(SB)}\, u_{SB}\, A_{SB}\, (T^{SB}_{He(ex)} - T_{He(in)}) + \rho_{f(g)}\, u_g\, A_g\, (T^{g}_{He(ex)} - T_{He(in)})] \tag{13}$$

where $\rho_{f(SB)}$ and $\rho_{f(g)}$ are the average helium purge densities in the solid breeder and gap regions and c_p is the specific heat of helium. Fig. 5 shows the variation of the amount of power removed by the purge flow as a fraction of the average fusion power per canister rod with the purge flow velocity.

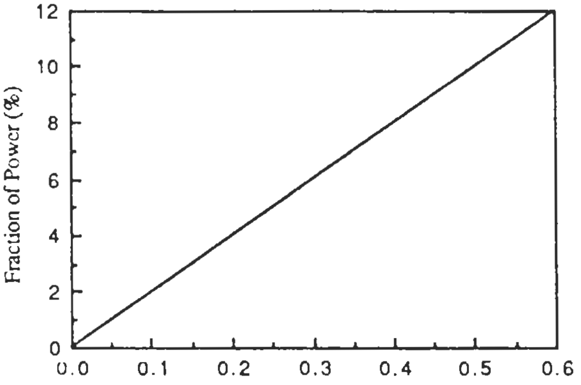

Figure 5. Power removed by the purge flow as a function of the purge flow velocity.

Finally, Fig. 6 shows the pressure drop in the rod as a function of the purge velocity for different particle diameters. The pressure drop was estimated using Ergun's correlation [6,7]:

$$\frac{\Delta p}{L} = 150 \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu u_0}{(\phi d_p)^2} + 1.75 \frac{(1-\varepsilon)}{\varepsilon^3} \frac{\rho u_0^2}{\phi d_p} \tag{14}$$

where L is the rod length, ϕ is the form factor, μ is the gas viscosity, and ρ is the gas density. The combination of low purge velocity and relatively large particle diameter leads to small pressure drops in the gap.

CONCLUSIONS

A concept using a pebble bed of Be with He is proposed for the thermal resistance gap required between the hot solid breeder and cold coolant for ITER designs. The concept is applicable to water-cooled or helium-cooled solid breeder and also to water-cooled LiPb blanket options. The proposed gap configuration has several advantages including the flexibility of setting the desirable thermal resistance by tailoring the bed characteristics, the possibility of controlling the effective thermal conductivity by adjusting the purge flow through the bed. The use of a purge flow also provides for tritium removal in the Be region and thus creates an additional purge barrier against tritium permeation from the solid breeder region. Finally, the purge flow can also help to remove the afterheat during shutdown conditions or in the event of a LOCA [10].

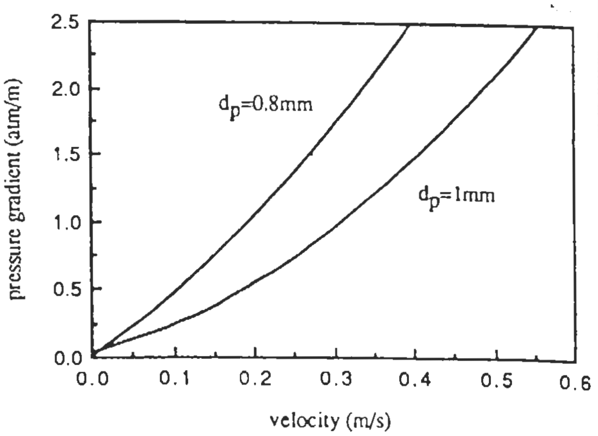

Figure 6. Pressure gradient in the sphere-pac solid breeder.

The maximum solid breeder temperature must be accurately predicted to allow for the most flexibility in case of power variation for both the low pressure low temperature water and helium designs. The effective thermal conductivity of the proposed Be particle bed must then be accurately predicted and reproducible. In addition, for additional flexibility to accommodate power variation, means to control the effective thermal conductivity such as the use of a flowing purge gas are desirable. For these reasons, due to the poor extrapolation of existing models predicting the effective thermal conductivity of beds to conditions other than those of the experiments on which they are based, experimental data are required for ITER type conditions. Key conditions that should be reproduced in such an experiment are the porosity (20-30%), the thermal conductivities of the gas and solid (He and Be), flowing He, the geometrical form of the particles, and the ratio δ_g/d_p of the gap.

ACKNOWLEDGEMENTS

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