ABSTRACT

The main design features of a new concept for solid breeder blanket thermal resistance gaps are described and analyzed. This 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 reviewed.

INTRODUCTION

Control of gap 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 a inert gas, such as He or Ar, or a mixture of both. However, this type of thermal gap, where small changes in the gap could substantially affect the solid breeder temperature, is not considered very attractive, particularly in designs with long pools or slabs where maintenance of the gap thickness under fusion conditions would 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-fueled devices. This concept is based on the use of a gap of a dispersion of solid and liquid 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 gas, allows for better uniformity and predictability of the thermal resistance.
3) The use of beryllium in a near-homogeneous mixture enhances the overall breeder 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 waste conditions without violating temperature constraints.
5) The 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 gas volume.

7) An additional barrier is provided against helium 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 Heflue volume fractions. Next, the analytical 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 cascades poloidally positioned side by side on the outboard region. Each cascades contains an array of rods in which the solid breeder and blister 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 B of thicken-

pack form whereas the three-zone configuration also includes an extra solid Bt 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 heat conduction, and the thermal conductivity of the solid is considered. For the solid breeder blanket, the temperature is calculated as a function of the temperature difference across the solid breeder blanket and the coolant. The temperature drop across the solid breeder blanket and the coolant is calculated using the following equation:

\[ \Delta T_{SB} = \frac{q_{SB}^2}{4k_{SB}} \]  

(1)

\[ \Delta T_{g} = \frac{q_{g}^2}{2k_{g}} + \frac{q_{SB}^2}{4k_{SB}} \]  

(2)

\[ \Delta T_{f} = \frac{q_{f}^2}{4k_{f}} + \frac{q_{SB}^2}{4k_{SB}} \]  

(3)

\[ \Delta T = \frac{q_{f}^2}{4k_{f}} + \frac{q_{SB}^2}{4k_{SB}} + \frac{q_{g}^2}{4k_{g}} \]  

(4)

where \( \Delta T_{SB} \), \( \Delta T_{g} \), \( \Delta T_{f} \), and \( \Delta T \) are the solid breeder, gap, film, and total temperature drops, respectively. \( k_{SB} \), \( k_{g} \), and \( k_{f} \) are the thermal conductivity of the solid breeder, gap, and film, respectively. The heat generation per unit volume in the solid breeder blanket is denoted by \( q_{SB} \), and the heat generation per unit volume in the gap and film is denoted by \( q_{g} \) and \( q_{f} \), respectively.

Figure 2 shows the gap and annulus thicknesses required to maintain a temperature drop of 350°C.

In spite of the existence of several formulations and approximations, Equation (3) cannot be predicted with desirable accuracy even if \( k_{SB}/\Delta T \) is omitted. Very complicated thermal processes bring an asymptotic character to theoretical models and to the correction and suppression of experimental data. Among the analytical models, the formula given by Kuno and Smith [12] is most popular (6,7). But predictions based on this model have only limited accuracy especially when \( k_{SB}/\Delta T \) is small (<10). For example, in Figure 3 a comparison of the calculated \( k_{SB}/\Delta T \) for a Breffle mix based on different correlations for the following conditions: show that the difference can be more than a factor of 2, for example, between the expressions from Kuno and Smith [12] and Watanabe and Vennerstein [18] in both He and Ar.

MODEL FOR THE EFFECTIVE THERMAL CONDUCTIVITY

The gap is a homogeneous 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 in-phase interactions and the complexity of processes, the heat transfer through the gap is considered as an effective conduction process.

The effective thermal conductivity, \( k_{g}^{eff} \), is a characteristic of the mix of macro-dispersed solid and gas which combines both their physical and geometrical properties. Under strictly state conditions, \( k_{g}^{eff} \) is a function of various parameters, as follows by the following equation:

\[ k_{g}^{eff} = \left( \frac{k_{g}}{k_{SB}} k_{SB} + \frac{k_{SB}}{k_{g}} k_{g} \right) \]  

(5)

where \( k_{SB} \) and \( k_{g} \) are the thermal conductivities of the gas and solid, \( k_{SB} \) and \( k_{g} \) are the effective thermal conductivities of the gas and solid, respectively.
SOLID BREEDER BLANKET THERMAL RESISTANCE GAPS

For the solid breeder for ITER blankets 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 expansion ($\beta_{b}$ in equation (5)) is minimalized. Similarly, the dependence on pressure ($\beta_{p}$) and wall effect ($\beta_{w}$) can be minimized for high helium pressure inside the gap and $\Delta \rho_{b}$ and for $\beta_{w}$ about 10. Note that for small particles and bed porosity, the local Knudsen numbers can be large and pressure variations can be used as a means of controlling the bed effective thermal conductivity.

Effect of Axial Layers

Formation of an axial layer on the Be spheres would affect $k_{b}$ and in turn $\Delta \rho_{b}$ through equation (5). The thermal conductivity of the solid spheres can be represented as a combination of the thermal conductivity of Be and BeO ($k_{Be}$ and $k_{BeO}$) [9],

$$k_{b} = k_{Be} (1 + B \frac{\beta_{p}}{\beta_{b}})$$

where $\Delta \rho_{b}$ is the thickness of the axial layer.

Table 1 shows the effective thermal conductivity for a Be/BeO gap as a function of the assumed axial layer thickness for $\beta_{p}=0$ and $\beta_{p}=0.4$. Because of the relatively high thermal conductivity of BeO, the effect of the axial layer is quite small. By comparison, the effect on a metal whose axial has low conductivity (such as Al) can be quite large.

<table>
<thead>
<tr>
<th>$\Delta \rho_{b}$/A</th>
<th>k_{Be}(A)/W/m.K</th>
<th>k_{Be}(A)/W/m.K</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4.2</td>
<td>4.2</td>
</tr>
<tr>
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<td>4.2</td>
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<td>0.5</td>
<td>4.2</td>
<td>4.2</td>
</tr>
<tr>
<td>1</td>
<td>4.2</td>
<td>4.2</td>
</tr>
</tbody>
</table>

The following thermal conductivities were used based on a relative temperature of 21°C:

$$k_{Be} = 4.2 \text{ W/m.K for Al}$$
$$k_{Be} = 16 \text{ W/m.K for BeO}$$
$$k_{b} = 121 \text{ W/m.K for Al}$$
$$k_{b} = 159 \text{ W/m.K for Be}$$

Flow Through the Gap

Conductivity of the gap purge could be used for both the solid breeder rod and in the annular Be/BeO gap. The use of a nitrogen purge through the rods is required for thermal removal of the blanket. It could also be potentially used to control the effective gap thermal conductivity for and for partial heat removal during loss-of-coolant accidents (LOCA) and/or shutdowns. The distribution of the average purge velocity between the solid breeder and the gap, $v_{gap}$ and $v_{b}$, is based on the ratio of vacuum removal from the solid breeder and gap, $Q_{vac} / Q_{gap}$.

$$\frac{Q_{vac}}{Q_{gap}} = \frac{v_{b}}{v_{gap}}$$

Where $Q_{vac}$ is the flow rate of gap and solid breeder regions. $u$ is the superficial velocity based on the total flow rate and full channel cross-sectional area. $A_{gap} = A_{gap} + A_{b}$ and $Q_{vac} / Q_{gap}$ will be much larger than $u_{b}$, $\text{kg/m}^2$.

The effective thermal conductivity of the gap with flowing helium, $k_{b}$ is given by [6,7],

$$k_{b}(A) = k_{b}(A) + B \beta_{p}$$

where

$$B = 0.11$$

$$B = 0.09$$

$D$ is the hydraulic diameter, $P_{f}$ is the Frictional number, and $R_{f}$ is the Reynolds number based on the pipe diameter.

$$R_{f} = \frac{u_{b} D}{v_{b}}$$

Both the gap region as well as the solid breeder are assumed to be in sphere-pellet form. Figure 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 $k_{b}$ of the Be region is small at $u_{b}$ is less than about 0.1 m/s. In this case, $R_{f}$ is small and the velocity-dependent term in Eq. (6) is much smaller than the static conductivity. Since $u_{b}$ is higher than $u_{b}$ by about an order of magnitude, based on equation (7), and because the solid breeder conductivity is in much lower, the effect of the purge on $k_{b}$ on the SB region is much more prominent. It is also important to note here that, according to experimental data, $k_{b}$ may show a stronger dependence on velocity in the region $D<2$ [3,7].

![Graph showing effective thermal conductivity vs. purge velocity](image)

**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 thermal after shutdown in or get out of a LOCA, the energy removal by jet purge and the pressure drop were calculated as a function of the purge velocity. The maximum possible temperature of the purge as the case of the solid breeder section. Therefore, it is equal to the average SB temperature.

$$T_{max}(A) = T_{SB}(max) = 473 K$$

Where $T_{SB}(max)$ is the maximum SB temperature at the jet center.

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

\[ T_{\text{exit}} = T_{\text{max}} - \frac{4Q}{2kA} \]  

(12)

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

\[ P_p = \frac{\rho v_d A_d}{C_H} \left( \frac{\Delta T_{\text{inlet}}}{\Delta T_{\text{outlet}}} \right) \]

\[ + \frac{\rho v_d A_d}{C_H} \left( \frac{T_{\text{inlet}} - T_{\text{max}}}{T_{\text{inlet}} - T_{\text{outlet}}} \right) \]  

(13)

where \( \rho \) and \( v_d \) are the average helium purge density in the solid breeder and gap regions and \( C_H \) is the specific heat of helium. Fig. 5 shows the variation of the amount of power removed by the purge flow as a function 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.](image)

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 for flows in packed beds [8,9]:

\[ \frac{P_d}{\rho g} = \frac{150}{D_p^2} \frac{1}{1.75} \frac{v_p^2}{u} + \frac{1.75}{D_p} \frac{v_p}{u} \]  

(14)

where \( L \) is the rod length, \( D_p \) is the form factor, \( \rho \) is the gas density, and \( u_p \) is the particle diameter. The correlation of low purge velocity and relatively large particle diameters lead to small pressure drops in the gap.

**CONCLUSIONS**

A concept using a pebble bed of Be with Be is proposed for the thermal resistance gap required between the hot solid breeder and cold coolant for ITER design. The concept is applicable to water-cooled or helium-cooled solid breeder and also to water-cooled Li,Pb blankets 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 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-gap solid breeder.](image)

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 water temperature and helium designs. The effective thermal conductivity of the proposed pebble bed must also 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 in conditions other than those of the experiments on which they are based, experimental data are required for ITER type conditions. Key conclusions that should be reproduced in such experiments are the porosity (20-30%), the thermal conductivities of the gas and solid (Be and Be), flowing He, the geometrical form of the particles, and the ratio \( \rho v_d \) of the gap.

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REFERENCES