STUDY OF EFFECTIVE SOLID-TO-SOLID CONTACT THERMAL RESISTANCE AND ITS APPLICATION TO SOLID BREEDER BLANKET DESIGN FOR ITER*

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ABSTRACT

Characterization of solid-to-solid contact thermal resistance is important for ITER solid breeder blanket designs utilizing sintered blocks of Be and/or solid breeder[1]. In order to fully assess the thermal performance of such blankets, including their ability to accommodate power variation, the thermal resistances of the Be/clad and solid breeder/clad contacts need to be characterized. In this paper, factors affecting the gas and solid conductances in the contact zone are analyzed. They include: roughness, contact pressure, temperature and curvature of restrained Be block. The study is carried out based on the models of Yovanovich[2] and Shlykov[3] and available experimental data from the literature. Recommendations are provided for the ITER solid breeder blanket design applications and for corresponding R&D requirements.

MATHEMATICAL DESCRIPTION OF THE MODELS

Yovanovich and Shlykov models [2,3] are chosen as representative of the better models available from the literature. The contact expressions developed by Yovanovich have been confirmed in plane-contact conditions and both the theoretical and semi-empirical variants of Shlykov model are often used in the USSR[3,4]. According to both models, the total conductance is the sum of the effective gas and solid conductances (thermal radiation effects are neglected under the assumption of low temperature);

$$a_{tot} = a_g + a_s \qquad (1)$$

Eq. (1) is widely used as a theoretical assumption and means that total conductance is the sum of two parallel and independent conductances: medium (gas) and solid-solid contact. In both models the effective gas conductance is defined as

$$a_g = k_g/\delta_e \qquad (2)$$

where δ_e is the equivalent thickness of the gas interlayer. If the nominal gap thickness g = 0 (direct contact of surfaces), Yovanovich model assumes:

$$\delta_e = y + 2j \qquad (3)$$

$$y = 1.184\, h_{r,eff}\, [\ln(-3.132\, P_c/Heff)^{0.547}] \qquad (4)$$

$$a_g = k_g/(y + 2j) \qquad (5)$$

Using the dimensionless parameter δ_e/δ_{max} and $\delta_{max}/2j$, Shlykov theoretical model defines a_g as:

$$a_g = k_g\, f(X)/(h_{r,1} + h_{r,2}) \qquad (6)$$

where:

$$f(X) \equiv \delta_e/\delta_{max}; \;\; X \equiv \delta_{max}/2j; \;\; \delta_{max} = h_{r,1} + h_{r,2} \qquad (7)$$

In the case g > 0, δ_{max} include the gap thickness, g:

$$\delta_{max} = h_{r,1} + h_{r,2} + g \qquad (8)$$

Note that in this case, the solid conductance is zero.

If j is constant, X is a function of the roughness of the contacting surfaces (here assumed to be steel and Be) and f(X) is a function of the material microstructure characteristics which is dependent on the material processing method. The correlations for f(X) are based on analysis of typical curves of base surfaces.[3,4] Reference [5] estimates the Be roughness $h_{r,Be}$, for sintered Be block with a porosity of 0.15 is to be about 17.5 µm and indicates that the roughness would increase with porosity. The function f(X) for this level of Be roughness may be estimated as for a rough surface from Refs. [3] and [4]:

$$f(X) \equiv \frac{10}{3} + \frac{10}{X} + \frac{4}{X^2} - 4\left(\frac{1}{X^3} + \frac{3}{X^2} + \frac{2}{X}\right) \ln(1 + X) \qquad (9)$$

For roughnesses of the order of 1 µm, f(X) is estimated based on the ground surface formula of Refs. [3] and [4]:

$$f(X) \equiv \frac{5}{2} - \frac{10}{X} - \frac{45}{X^2} - \frac{30}{X^3} + 30\left(\frac{1}{X^4} + \frac{2}{X^3} + \frac{1}{X^2}\right)\ln(1 + X) \qquad (10)$$

The solid contact conductance, a_s, based on Yovanovich model is:

$$a_s = 1.25\, \bar{k}\, m(P_c/Heff)^{0.95}/h_{r,eff} \qquad (11)$$

where $\bar{k}$, the effective solid thermal conductivity (W/m-k), m the effective absolute surface slope, and $h_{r,eff}$, the effective roughness (m) are given by:

$$\bar{k} = 2\, k_{Be}\, k_{st}/(k_{Be} + k_{st}) \qquad (12)$$

$$m = (m_{Be}^2 + m_{st}^2)^{1/2} \qquad (13)$$

$$h_{r,eff} = (h_{r,Be}^2 + h_{r,st}^2)^{0.5} \qquad (14)$$

Based on Shlykov model, a_s is given by:

$$a_s = 1.6 \times 10^4\, \bar{k}\, f(P_c/3S_{ft})/Y_k \qquad (15)$$

where, assuming a relative contact area equivalent to $(P_c/3S_{ft})$:

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* This work was supported by the U.S. Department of Energy under contract # DE-FG03-86ER52123.

$$f(P_c/3S_{ft}) = \frac{P_c/3S_{ft}}{1-1.41(P_c/3S_{ft})^{0.5} + 0.3(P_c/3S_{ft})^{1.5}} \quad (16)$$

Y_K is a conical shape roughness factor which varies typically between 1.025 and 1.075. The parameters used in the above equations are described in the Nomenclature Section.

Applying his theoretical model to experimental data, Shlykov proposed the following semi-empirical version of his model.[3]

$$a_g = k_g\, f(X)/2(h_{r,1} + h_{r,2}) \quad (17)$$

$$a_s = 8 \times 10^3\, \bar{k}(P_c\, M/3S_{ft})^{0.86} \quad (18)$$

where M is a nondimensional constant which depends on roughness (μm):

$$\left.\begin{array}{l} M = 1 \text{ if } (h_{r,1} + h_{r,2}) \geq 30\mu m \\ M = [30/(h_{r,1}+h_{r,2})]^{1/3} \text{ if } 10\mu m < (h_{r,1}+h_{r,2}) < 30\mu m \\ M = 15/(h_{r,1} + h_{r,2}) \text{ if } (h_{r,1} + h_{r,2}) \leq 10 \end{array}\right\} \quad (19)$$

Note that these expressions may be used only for metal-to-metal contacts and are limited to values of $P_c/3S_{ft}$ of about 0.02 - 0.025 and temperatures lower than $0.3T_{melt}$. Comparison of the two Shlykov approaches is shown in Fig. 1. Note also that in both eqs. (15) and (18) the numerical constants are expressed in m^{-1}. According to correlations (19), for $h_{r,Be} = h_{r,st} = 1\mu m$, $M = 15/2 = 7.5$; and for $h_{r,Be} = 17.5\mu m$ and $h_{r,st} = 1\mu m$; $M = 30/18.5 = 1.175$.

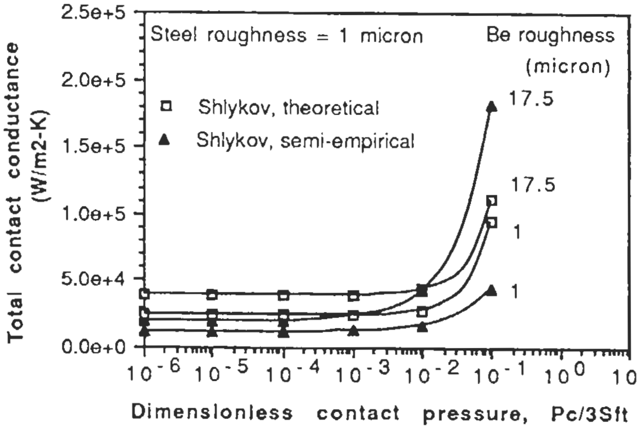

Figure 1: Total contact conductance as a function of Be/Steel dimensionless contact pressure based on Shlykov theoretical and semi-empirical models.

The difference in the total contact conductances estimated from the two approaches, as shown in Fig. 1, can be traced back to the calculations of the gas and solid conductance components. Both the theoretical and semi-empirical expressions for the gas conductance (eqs. (6) and (17)) are independent of contact pressure. However, the semi-empirical expression yields lower a_g values for a given roughness because it takes into account the surface waviness when estimating the δ_{max} used in calculating f(X).[3,4] The solid conductance calculated from the semi-empirical expression (eq. (18)) differs also from that calculated from the theoretical expression (eq. (15)) since it takes into account the surface roughness (through M) and since it is proportional to $(P_c/3\, S_{ft})$ to a lower power (0.86 instead of 1). The combined effect of the a_s and a_g calculations on the total contact conductance results in the semi-empirical estimates being lower than the theoretical estimates for low relative contact pressure ($(Pc/3\, S_{ft}) < 10^{-3}$) where a_g has a predominating effect. As the contact increases, the semi-empirical estimate of a_{tot} becomes higher than the theoretical estimate for low surface roughness. The semi-empirical model of Shlykov is chosen for the detailed analysis and comparison to Yovanovich semi-empirical correlation presented hereafter.

PARAMETRIC ANALYSIS

From both Shlykov and Yovanovich models, key parameters affecting the gas, solid and total conductances at the solid-to-solid interface include the gap thickness, the surface roughness, the ratio of contact pressure to the material hardness or tensile stress. The effect on the interface conductance of each of these parameters is discussed in this section.

The gap thickness at the Be/steel interface is particularly important for the performance of the US ITER solid breeder design[1] since it could appreciably vary during operation because of swelling and thermal expansion. The sum of the gap thickness and surface roughnesses represents the characteristic heat conduction length, L_c which when compared to the mean free path of the gas, λ, determines the Knudsen number ($Kn = \lambda/L_c$). For very small Knudsen number (about 10^{-3} and lower), the gas can be treated as a continuum and ordinary conduction occurs. As the Knudsen number is increased, non-continuum effects play an increasing role until conduction is fully in the free-molecule flow regime. Evaluation of Kn as a function of the gap thickness for helium at 1 atm and 400°C shows that a gap thickness of about 250 microns or more is required for Kn to be about 10^{-3} or lower and for ordinary conduction to prevail.

The corresponding gas conductance based on Yovanovich model is shown in Fig. 2 as a function of the gap thickness and the Be roughness for a steel roughness of 1 micron. For g = 0, the gas conductance is effectively a function of the roughness only and is much higher for the lower roughness value. It then decreases rapidly as g is increased and is in effect inversely proportional to g at higher gap thicknesses where the roughness is relatively too small to have any significant effect.

Mechanical properties of the contacting materials, in particular the hardness and the tensile stress can affect the interface conductance. Yovanovich includes the ratio of contact pressure to microhardness (P_c/H_{eff}) in this expression for determining both the gas and solid conductances for solid-to-solid contact (Eqs. (4) and (11)).

Shlykov does not include mechanical properties in the determination of the gas conductance but expresses the solid

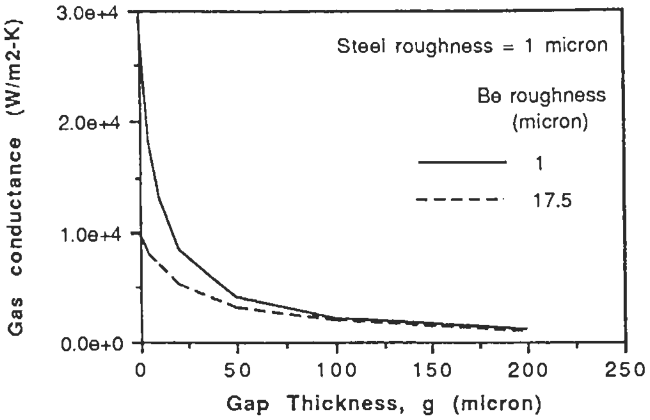

Figure 2: Gas conductance as a function of gap thickness for different Be roughnesses.

conductance (see Eq. (18)) as a function of the ratio of contact pressure to the ultimate tensile strength ($P_c/3S_{ft}$). Based on Refs. [3] and [4], 3 S_{ft} can be reasonably considered as a representation of H_{eff} and it is assumed here that:

$$P_c/H_{eff} \approx (P_c/3S_{ft}) \qquad (20)$$

This assumption is very helpful when analyzing cases with Be since data on its ultimate tensile strength is more readily available than data on its hardness.

Figure 3 shows the effect of the ratio (P_c/H_{eff}) on the gas conductance based on Yovanovich model for g = 0, $h_{r,st} = 1$ µm and $h_{r,Be} = 1$ and 17.5 µm. The gas conductance can be seen to increase with P_c/H_{eff}. As a means of comparison, corresponding estimates of the gas conductance based on Shlykov model are also shown. For ratios of P_c/H_{eff} of up to at least 0.1, Yovanovich predictions are decreasingly lower than those of Shlykov for the 17.5 µm Be roughness but are increasingly higher for $h_{r,Be} = 1$ µm. Both models indicate that a_g is much higher for the smoother surface.

Figure 4 shows the effect of the ratio (P_c/H_{eff}) on the solid conductance based on both models. Both models show a_s increasing with decreasing roughness and both indicate a sharp increase in a_s when Pc/H_{eff} reaches a value of about 10^{-2} - 10^{-3}, especially for the lower roughness.

Figure 5 shows the effect of (P_c/H_{eff}) on the total contact conductance as a summation of a_g and a_s based on both models for Be roughnesses of 1 µm and 17.5 µm. Under both models, a_{tot} behaves similarly to a_s for higher values of Pc/H_{eff} with a substantial increase observed when Pc/H_{eff} reaches about 10^{-2}, in particular for the low roughness case.

This indicates that the contribution of a_s to a_{tot} becomes dominant when the ratio of P_c/H_{eff} reaches about 10^{-2} depending on the roughness. It is interestng to note that for $h_{r,Be} = 17.5$µm the largest diffference between the two model predictions occurs at low values of Pc/H_{eff} (Shlykov's model yielding a value of a_{tot} about 4 times larger than that of Yovanovich for $Pc/H_{eff} = 10^{-6}$). For $h_{r,Be}$

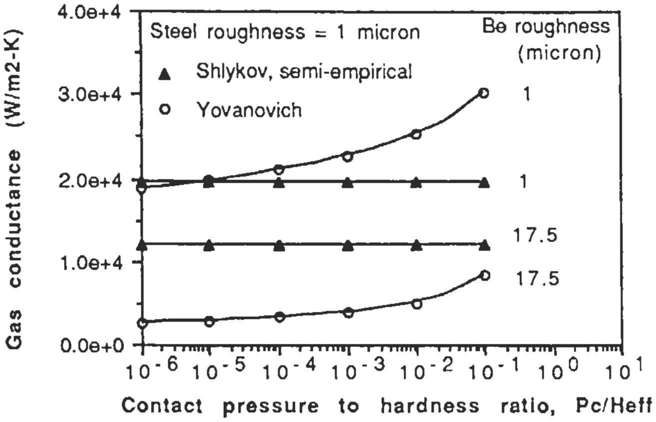

Figure 3: Gas conductance as a function of Be/steel contact pressure to hardness ratio for different Be roughnesses based on Yovanovich and Shlykov models.

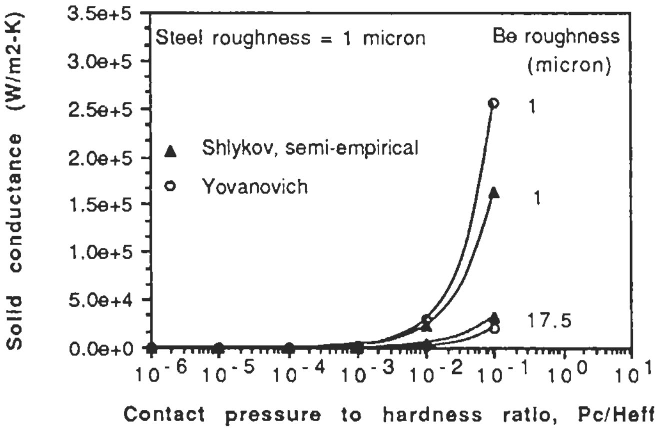

Figure 4: Solid conductance as a function of Be/steel contact pressure to hardness ratio for different Be roughnesses based on Yovanovich and Shlykov models.

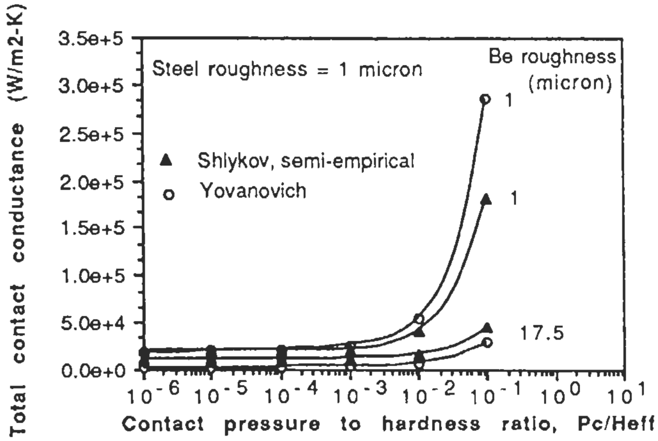

Figure 5: Total contact conductance as a function of Be/steel contact pressure to hardness ratio for different Be roughnesses based on Yovanovich and Shlykov models.

= 1μm, the largest difference occurs at higher values of Pc/H_{eff}. Yovanovich's prediction being about 50% higher than that of Shlykov's for $Pc/H_{eff} = 0.1$.

EFFECT OF OPERATING CONDITIONS

Operating conditions can significantly affect the thermal conductance of the Be/steel interface. In this section, effects on this interface conductance of temperature, mechanical bending and mechanical constraint of Be blocks are examined.

First the effect of the temperature dependency of determinant material properties on the interface conductance is considered. The thermal conductivity of Be[1], 316 stainless steel[6] and the effective combined solid thermal conductivity based on eq. (12) are shown in Fig. 6 as a function of temperature. Whereas the thermal conductivity of beryllium decreases appreciably with temperature, that of steel increases slightly as does the effective solid thermal conductivity. The ultimate tensile strength of Be also varies with temperature according to the following expression.[5]

$$S_{ft}\ (\mathrm{MPa}) = (450/\sqrt{d_g})\ \exp(-5\varepsilon)\ \ln(9200/T) \qquad (21)$$

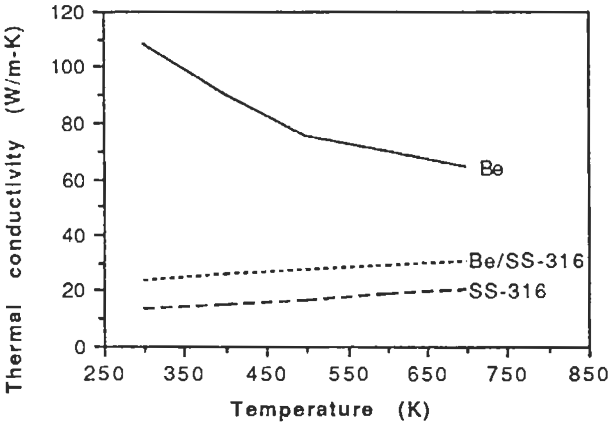

Figure 6: The influence of temperature on the thermal conductivity of SS-316, Beryllium (0.85TD) and on the effective solid thermal conductivity of "Be-SS" interface contact.

Fig. 7 shows the effect of temperature on the solid thermal conductivity, $\bar{k}_{(n)}$, ultimate tensile strength, $S_{ft(n)}$, and solid contact conductance, $a_{s(n)}$, normalized to their respective values at 300 K. The solid thermal conductivity increases with temperature while the ultimate tensile strength decreases but their combined effect causes the solid conductance to markedly increase with temperature. For example, raising the temperature from 500K to 700K causes about a 14% increase in $\bar{k}$ and a 9% decrease in S_{ft} which result in approximately a 28% increase in a_s. It is interesting to note the relative increase in a_s is about the same for both models. The results obtained are in reasonable agreement with experimental data on the temperature effect on SS/SS contact conductance (with $h_r = 0.7$ and 1.2 μm).[5]

These results are quite beneficial when applied to the blanket design since an increase in temperature results in an increase in conductance due to the combined temperature effects on conductivity and ultimate strength. This could reduce the temperature drop at the interface thereby allowing higher temperature operation and passive power accommodation based on maintaining the solid breeder temperature within its allowable window.

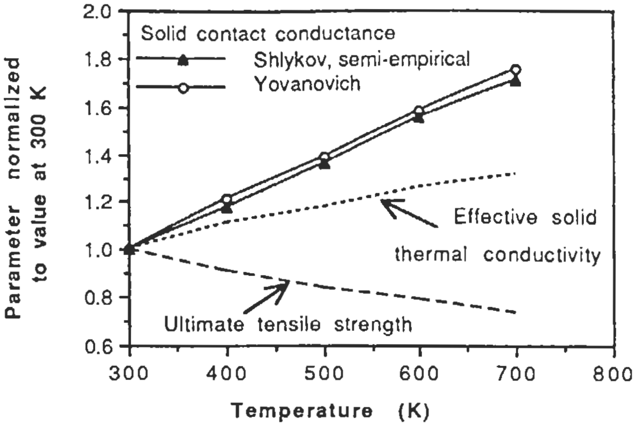

Figure 7: The influence of temperature on the effective solid thermal conductivity, Be ultimate thermal strength and the resulting solid contact conductance of the Be-SS interface (normalized to their values at 300K) for $h_{r,Be} = h_{r,st} = 1$ μm.

In the design, each Be sintered block will experience a thermal gradient. If the blocks are not constrained, they will curve to relieve the stress due to differential thermal expansion, resulting in a slight deflection at the Be/SS interface. The effect of the maximum bending deflection, Δ_{max}, on the Be/SS interface solid conductance was estimated from Malkov et al's comparison of in vacuo experimental data to Shlykov's model predictions.[4] This relative change is a function of the ratio of Δ_{max} to the sum of the surface roughnesses.

For the gas conductance, the effect of bending was evaluated from Malkov et al.,'s comparison of experimental data to the corresponding predicted values for He and Ar, as shown below:[4]

$$\frac{a_g(\Delta_{max} + \Sigma h_r)}{k_g} = f\left(\frac{\Delta_{max} + \Sigma h_r}{2j}\right) \qquad (22)$$

Where Σh_r represents the sum of the roughnesses of the contact surfaces.

Figures 8, 9 and 10 show the effect of Δ_{max} on the solid, gas and total conductances respectively for a Be/steel interface for different ratios of P_c/H_{eff} and Be roughnesses. From Fig. 8, for low values of P_c/H_{eff} (10^{-3} or lower), the effect of increasing Δ_{max} results in a gradual decrease of a_s. However, for higher ratios of P_c/H_{eff} (0.1), the decrease in a_s is large as Δ_{max} is increased from 0 to 50 μm. This is to be expected since the initial value of a_s is much larger for high ratios of P_c/H_{eff} which results in good solid contact conductance. Thus, the relative decrease as a gap is inserted is much larger. The decrease is slightly lower for the larger Be roughness case.

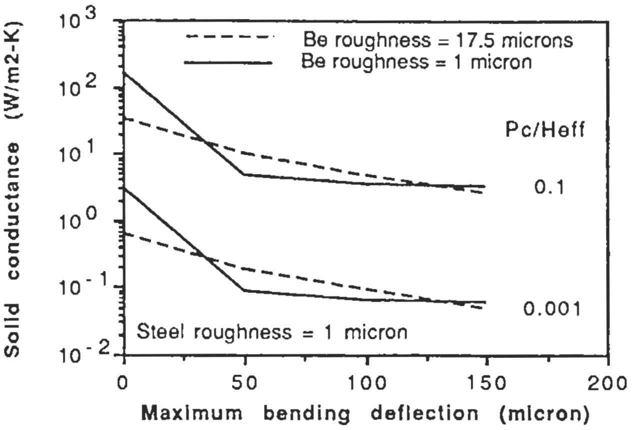

Figure 8: Solid conductance as a function of Be maximum bending deflection and Be/Steel contact pressure to hardness ratio for different Be roughnesses based on Malkov, et al.[4]

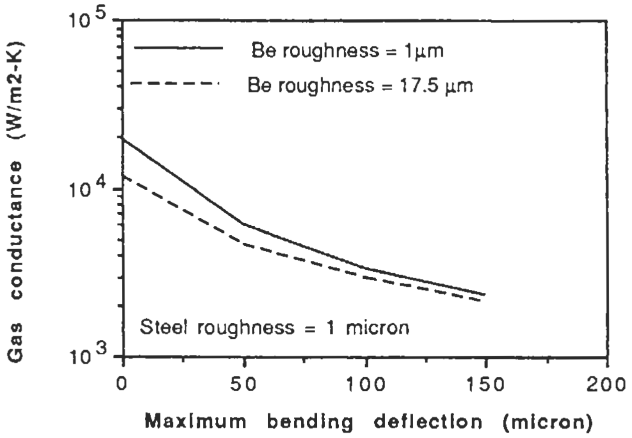

Figure 9: Gas conductance as a function of Be maximum bending deflection based on Malkov, et al.[4]

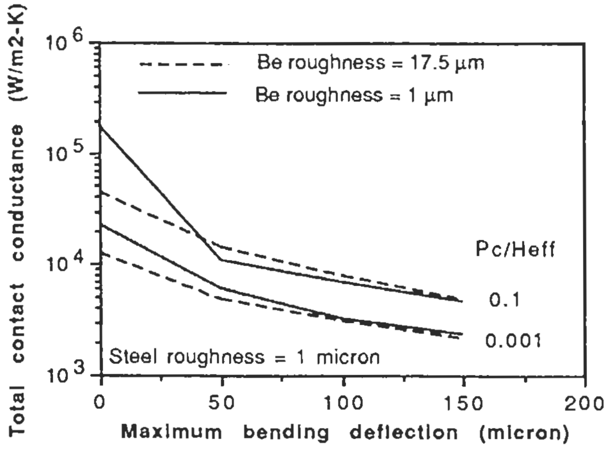

Figure 10: Total contact conductance ratio as a function of Be maximum bending deflection and Be/Steel contact pressure to hardness ratio for different Be roughnesses based on Malkov, et al.[4]

From Fig. 9, a_g decreases with Δ_{max} in a way similar to its decrease with g from Fig. 2, which is to be expected. The combination of decreases in a_s and a_g as Δ_{max} increases cases a large decrease in a_{tot} initially. When Δ_{max} is increased from 0 to 50 µm, a_{tot} decreases substantially depending on the roughness and ratio of P_c/H_{eff}. This is an important result since it suggests that a 50 µm bending deflection can increase the contact temperature drop by up to a factor of 15 assuming full contact initially and should be considered when characterizing blanket performance under different temperature levels.

Finally, the effect of thermal expansion or swelling on fully constrained Be blocks is considered as a limiting case by assuming that the constrained expansion results in higher stresses and, hence, on higher contact pressure at the Be/steel interface.

The following expression was used:

$$P_c = \frac{E}{3(1-2v)} \frac{\Delta V}{V} \tag{23}$$

The calculations show that for this limiting fully constrained case, a volumetric expansion of only about 0.6% causes a $P_c/3S_{ft}$ of 1. In a design, space would have to be provided to accommodate volumetric expansion and in addition the clad would probably deflect under excessive pressure at the contact point. Thus, the effective volumetric expansion causing the pressure would be significantly lower than the actual volumetric expansion. The benefit of increasing contact pressure due to any constrained expansion can be seen from Fig. 5 where a_{tot} increases significantly with increasing P_c/H_{eff} particularly for lower roughnesses.

SUMMARY

The thermal conductance at the Be/SS clad interface of the ITER solid breeder blanket of Ref. [1] was analyzed based on Yovanovich and Shlykov semi-empirical models. Such contact resistance is in general a more important factor for plane-surface contacts than for sphere contacts as part of a packed bed for example where depending on the ratio of gas to solid thermal conductivity, only a fraction of the heat flows through the contact.[7-9] The predictability of the interface conductance can be very important in this blanket application particularly if the temperature drop across the interface is a significant fraction of the total temperature drop between the solid breeder and coolant, since any variation in its value would directly affect the solid breeder temperature which needs to stay within its allowable window. The temperatures, roughness, ratio of contact pressure to material hardness and nominal gap thickness were identified as three key parameters in determining the total interface conductance as the sum of the solid and gas conductances.

Both models showed that the total conductance increases with decreasing roughness and with increasing P_c/H_{eff}. Shlykov's model tends to predict higher values of a_{tot} for high roughness, up to a factor of 4 higher than Yovanovich's for P_c/H_{eff} of 10^{-6} or lower and $h_{r,Be}$ of 17.5μm. Yovanovich's model tends to predict higher values of a_{tot} for lower roughness, 50% or higher than Shlykov's for P_c/H_{eff} of 0.1 or higher and $h_{r,Be}$ of 1 μm. In general, uncertanties for predicting lower values of a_{tot} are more of a concern since any change in the correspondingly higher interface temperature drop would have a greater effect on the solid breeder operating temperature.

The effect of operating conditions on the interfacial conductance of blanket operation was assessed. In particular, the temperature level and Be block deflection occurring for thermal stress relief were viewed as two key factors and their effect on the interfacial conductance was analyzed. The results show that the effective solid conductivity increases with increasing temperature while the ultimate tensile strength (assumed to be representative of the hardness) decreases, both effects continuing to cause the total contact conductance to increase. This is beneficial when applied to the blanket case since it would help on accommodating power increases. The results also indicate that Be block deflection can substantially reduce the interfacial conductance to an extent dependent on the size of the deflection, the contact pressure and the roughness. For example, the total interfacial conductance can be reduced by up to a factor of 15 when the bending deflection increases from 0 to 50 μm for steel and Be roughnesses of 1 μm. Such effects can be accounted for in the design if properly characterized.

The above discussion indicates the importance of adequately accounting for the effect of different parameters such as the temperature, roughness and contact pressure in predicting the contact conductance. The relatively large variation between the predictions by the two models considered particularly at low values of P_c/H_{eff}, suggests that the characterization of the contact conductance should be done experimentally using the prototypical materials from which an experimentally-based model could then be developed for blanket analysis application.

NOMENCLATURE

a_g, a_s and a_{tot} are gas, solid contact and total gap conductances;
d_g = material grain diameter
E = Young's modulus
g = nominal gap thickness
h_r = mean roughness of surface
$h_{r,eff}$ = effective roughness defined by eq. (14)
H_{eff} = effective material microhardness
j = gas temperature jump distance
k = thermal conductivity

$\bar{k}$ = effective solid thermal conductivity of contacting surfaces
Kn = Knudsen number
M = parameter based on surface roughness, defined by eq. (19)
m = effective absolute surface slope
P_c = contact pressure
T = temperature
T_{melt} = melting point temperature
$\Delta V/V$ = volumetric expansion of Be block
X = geometrical characteristic in Shlykov model
y = mean plane separation of surfaces
Y_k = conical shape roughness factor
S_{ft} = ultimate tensile strength of material
Δ_{max} = maximum bending deflection
δ_e = equivalent thickness of gas
ε = porosity volume fraction
υ = Poisson's ratio

Subscripts:
Be = beryllium
c = contact
e = equivalent
eff = effective
g = gas
(n) = normalized to value at 300K
r = roughness
s = solid
st = steel
tot = total
1,2 = contacting surfaces

REFERENCES

1. U.S. Technical Report for the ITER Blanket/Shield - A. Blanket", ITER-TN-BL-5-0-3, Garching, FRG, (July - November, 1990).
2. T.E. Lemczyk and M.M. Yovanovich, "New Models and Methology for Predicting Thermal Contact Resistance" Heat-Transfer Engin., V.8, N2 (1987).
3. Ju.P. Shlykov, E.A. Ganin, S.N. Tsarevsky, "Contact Thermal Resistance", Energia, Moskow (1977) (in Russian).
4. V.A. Malkov et al., "Contact Heat Transfer in Gas Turbens and Power Installations", Moskow, (1978) (in Russian).
5. M.S. Billone and S. Majumbar, "Thermomechanical Analysis of the U.S. Solid Breeder Design", ANL, (March 5, 1990).
6. "Blanket Comparison and Selected Study", ANL/FPP-83-1, V. 1 (1983).
7. P. Adnani, et al., "Modeling of Effective Thermal Conductivity for a Packed Bed," UCLA-FNT-29 (November 1989).
8. Z. R. Gorbis, et al., "Parametric Analysis of Packed Bed Effective Conductivity Using Zone Model:, UCLA-FNT-38, (March 1990).
9. S. W. Tam and C. E. Johnson, "Interfacial Roughness and the Thermal Conductivity of a Sphere-Pac Bed", Advances in Ceramics, V. 27 (1990).