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Interface conductance between roughened Be and steel under thermal deformation

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Abstract

Predictability and control over temperatures and stresses are necessary in order to assure acceptable tritium release, component reliability and lifetime in solid breeder blankets. These blankets usually contain beryllium multiplier in either pebble-bed or solid block forms. For the solid block forms, uncertainties remain in the prediction of the thermal resistance between the Be and its cladding. Several parameters are important, including surface roughness and flatness, background gas pressure, and external loads which may result from blanket thermal deformations and/or pressure stresses. Differential thermal deformation between Be and steel can cause separation to occur between the two solid surfaces, which could seriously degrade the heat transfer. Existing models and data for solid–solid conductance show inconsistencies, even for steel surfaces. Little data or none exists for the Be–steel system, in which differential surface deformations are expected. In this work, we describe a new model which incorporates the combined influences of thermal deformation and contact pressure. Data were taken with small Be specimens as a function of the relevant parameters. The results show that the inclusion of non-conforming surfaces provides a richer range of behavior. Thermal deformations degrade the heat transfer by about a factor of two from flat surfaces, but this effect tends to decrease above about 100 kW m^{-2}. Contact pressure (above about 1 MPa) between the two materials can effectively maintain good conductance. The flatness and roughness of the surfaces are the most critical parameters. The work also demonstrates the large degree of variation in conductance with background gas pressure.

1. Introduction

Beryllium has been proposed in a number of recent blanket designs as a neutron multiplier and/or thermal barrier region between the breeder and coolant. In one form, the beryllium is used as solid blocks contained within a steel cladding material [1]. The heat transfer in such an arrangement depends on the interface conductance between the beryllium blocks and cladding. Small deformations could open up a gap large enough to result in very large temperature rises and non-uniformities throughout the blanket, especially at low contact pressures. Both modeling and experiments have been performed to characterize the interface conductance as a function of the key parameters, including bulk material properties, surface roughness, background-gas composition and pressure, heat flux and external contact pressure.

An experimental apparatus was constructed to provide the necessary environmental conditions. One-inch diameter Be and 304 stainless steel specimens are placed between a 500-W heater and the coolant. This provides heat fluxes as high as 1 MW m^{-2}. The specimen surfaces were grit-blasted with Al_2O_3 powders to

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produce roughness with r.m.s. values from 0.5 to 5 μm. The background-gas composition and pressure are maintained within a vacuum bell jar with pressures of 10–760 Torr. A hydraulic ram press provides external contact pressures up to 20 MPa. Data have been collected for various specimens as a function of gas pressure, contact pressure and heat flux.

Several simple models have been assembled from the literature and were used to compare with the data. However, existing models do not account for the combined effects of thermal deformations and external pressure. Therefore, a new model was developed to include these effects. The new model was compared against existing models and data.

Based on preliminary results, several conclusions can be made:

(1) Surface roughness is an important factor in both the absolute value of conductance and the dependence on contact pressure and thermal deformation. Rougher surfaces tend to exhibit lower conductances, but are much less sensitive to small changes in environmental conditions.

(2) Thermal deformation in 1″-diameter specimens easily exceeds the surface roughness, and is therefore an important factor. The amount of contact pressure required to overcome these deformations is large, and may be impractical in fusion reactor blankets.

(3) Gas pressure provides an effective means to adjust the interface conductance. Changing the background He pressure from 100 to 760 Torr produced a factor of three change in conductance between Be and steel.

2. Modified model for interface conductance

Several models exist for predicting solid-to-solid contact conductance. An assessment was performed in Ref. [2] for two of the most developed models by Shlykov et al. [3] and Lemczyk and Yovanovich [4]. The assessment concluded that neither model was clearly superior in all cases; the relative accuracy depends on the range of conditions assumed. Both models include roughness, external loads, and separate terms for gas and contact conductances: $h = h_g + h_c$, where h_g is the "gas conductance" and h_c is the "contact conductance". No known existing model includes the combined effect of thermal deformation and external load.

When the two surfaces are composed of the same material and the heat flux through both is equal, then the surfaces remain conforming even under thermal deformation. Differential thermal deformation occurs when the two surfaces are composed of different materials with different thermal expansion coefficients and conductivities.

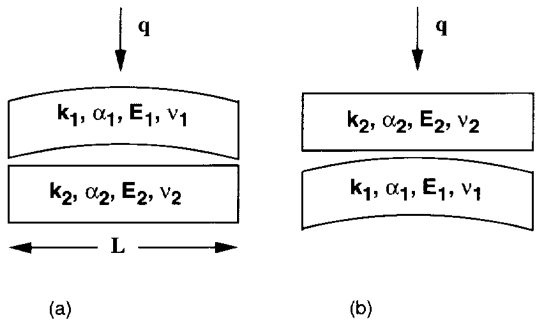

Fig. 1. Geometry of the contact zone: (a) edge contact; (b) center contact.

The Yovanovich model [4,5] was chosen as a starting point for an improved model which includes the geometric effects of thermal expansion and external loads. The roughness-averaged mean separation between the surfaces is computed for a one-dimensional cylindrical geometry with concentrically loaded disks under a uniform axial heat flux. This is used to recompute the gap conductance integral and the contact area. Since the contact area decreases under thermal expansion, the equivalent contact pressure is re-evaluated based on the true contact area.

Fig. 1 shows the geometry of the disks, where the thermal conductivity k, thermal expansion coefficient α, elastic modulus E and Poisson ratio v may be different for materials 1 and 2. Two cases are possible, depending on the direction of the heat flux and the properties of the two materials: (a) deformation results in edge contact and a gap in the center, and (b) deformation results in center contact and a gap around the edges.

In this derivation, we assume that the disks are axisymmetric, concentrically loaded thin plates, and that thermal and pressure deformations are independent. In that case, the peak deformation $\delta_{\max}$ due to thermal plus pressure loading is [6]:

$$\delta_{\max} = \frac{Q}{2\pi}\left(\frac{\alpha_1}{k_1} - \frac{\alpha_2}{k_2}\right) - \frac{PL^4}{128}\left[\frac{1}{D_1}\left(1 + \frac{11 - v_1}{21 + v_1}\right) + \frac{1}{D_2}\left(1 + \frac{11 - v_2}{21 + v_2}\right)\right] \tag{1}$$

where P is the uniform pressure, Q is the total heat rate in W, α is the coefficient of linear expansion, k is the thermal conductivity, v is the Poisson ratio and D is the bending modulus:

$$D = \frac{Eh^3}{12(1 - v^2)} \tag{2}$$

where h is the disk thickness and E is the elastic modulus.

For the case in which $\alpha_1/k_1 \gg \alpha_2/k_2$, such as for steel and Be, then one of the surfaces can be assumed to remain essentially flat. The final assumption is that the shape of the deformed disks remains spherical. In the future, this approximation could be improved to account for the exact deformed surface shapes.

Given these assumptions, the separation distance as a function of the radial distance from the center r for case (a) is given by:

$$\delta_{\mathrm{a}} = \delta_{max} - \frac{L^2}{8\delta_{max}}\left\{1 - \left[1\left(\frac{8\delta_{max}}{L^2}\right)^2\right]^{0.5}\right\} \tag{3}$$

For case (b), the separation is given by:

$$\delta_{\mathrm{b}} = \delta_{\mathrm{max}} - \delta_{\mathrm{a}}$$

2.1. Modified contact conductance

For the case of no differential thermal deformation, the relation for the contact conductance (the portion due to solid–solid contact) is [5]:

$$h_{\mathrm{c}} = \frac{1.25mk_{\mathrm{s}}}{\sigma}\left(\frac{P}{H}\right)^{0.95} \tag{5}$$

where σ is the r.m.s. roughness between the two surfaces, m is the mean asperity slope and H is the Brinell hardness of the softer surface (which dominates the mechanical interaction). Following deformation, the applied pressure is not evenly distributed over the disk surface, but rather concentrated in the region of contact. Only part of the deformed surface remains in contact with the flat disk, allowing contact conductance only in the region of contact. The region of contact is approximated by summing the area where the r.m.s. roughness exceeds the gap spacing based on Eqs. (3) and (4). This area is an annulus with outer radius $L/2$ and inner radius x_{c} determined by setting $\delta = \sigma$ in Eq. (3). The pressure term in Eq. (5) must be divided by the area ratio, yielding the following expressions:

$$\frac{A_{\mathrm{contact}}}{A_{\mathrm{total}}} = 1 - \frac{L^2}{16\delta_{\mathrm{max}}{}^2}\left[1 - \left(1 - \frac{\delta_{\mathrm{max}} - \sigma}{L^2/8\delta_{max}}\right)^2\right] \tag{6}$$

$$h_{\mathrm{c}} = \frac{A_{\mathrm{contact}}1.25mk_{\mathrm{s}}}{A_{\mathrm{total}}\quad\sigma}\left(\frac{A_{\mathrm{total}}\ P}{A_{\mathrm{contact}}H}\right)^{0.95} \tag{7}$$

This is almost identical to Eq. 5, indicating that the effect of decreased contact area essentially cancels with the effect of increased contact pressure for this level of approximation.

2.2. Modified gas conductance

Following the treatment of Yovanovich, the gas conductance for two *conforming* disks is given by:

$$h_{\mathrm{g}} = \frac{k_{\mathrm{g}}}{\sigma}I_{\mathrm{g}} \tag{8}$$

where I_{g} is the gap conductance integral, defined by:

$$I_{\mathrm{g}} = \frac{1}{\sqrt{2\pi}}\int_0^{\infty}\frac{\exp[-0.5(Y/\sigma - u)^2]}{u + M/\sigma}\mathrm{d}u \tag{9}$$

and Y is the mean separation. For the case with conforming surfaces, the relation for Y/σ is given by:

$$\frac{Y}{\sigma} = 1.184\left[-\ln\left(3.132\frac{P}{H}\right)\right]^{0.547} \tag{10}$$

For the case with differential thermal deformation, the following modification is proposed for Y/σ:

$$\frac{Y}{\sigma} = \frac{1}{\sigma A}\int \delta\,\mathrm{d}A \tag{11}$$

In general, there will be two regions: (a) separation smaller than the roughness, $\delta \leqslant \sigma$, and (b) separation larger than the roughness $\delta > \sigma$. In region (a), Eqs. (9) and (10) are used with the modification to the pressure term described above, which accounts for the local concentration of pressure in the contact zone. In region (b), Eq. (11) is used to account for the increased gap spacing due to deformation.

The average value of Y/σ over the entire surface is obtained by area averaging:

$$\frac{Y}{\sigma} = \frac{A_i}{A_{\mathrm{total}}}\frac{Y_i}{\sigma} + \frac{A_{ii}}{A_{\mathrm{total}}}\frac{Y_{ii}}{\sigma} \tag{12}$$

2.3. Total conductance

Finally, the total conductance is found from the parallel sum of conductances:

$$h_{\mathrm{c}} = \frac{A_{\mathrm{contact}}}{A_{\mathrm{total}}}\frac{1.25mk_{\mathrm{s}}}{\sigma}\left(\frac{A_{\mathrm{total}}}{A_{\mathrm{contact}}}\frac{P}{H}\right)^{0.95} + \frac{k_{\mathrm{g}}}{\sigma}I_{\mathrm{g}} \tag{13}$$

Fig. 2 shows model predictions for the total interface conductance as a function of contact pressure for the Be–steel system under 120 kW m^{-2} of heat flux and 1 atm of He. The solid contact terms are plotted as well. For both surfaces, the contact conductance is small. As the roughness is increased, the total conductance drops significantly. At the same time, the variation with

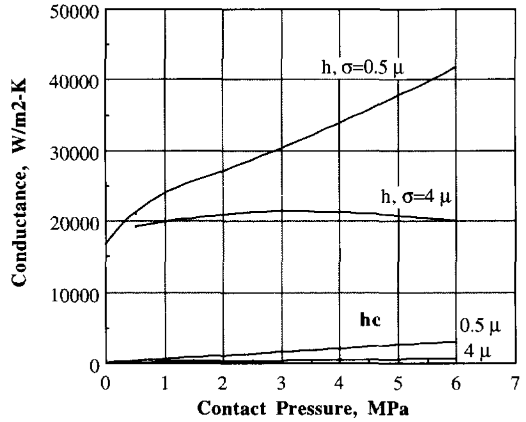

Fig. 2. Model predictions for a Be–steel interface with $\epsilon = 0.5$ and $\epsilon = 4$ μm.

contact pressure is reduced. This shows the tendency of roughness to add a form of "compliance" to the interface.

At high contact pressure for the rougher case, the conductance appears to decrease slightly. This effect may be due to the distribution of the load over a larger contact area, giving smaller *local* contact pressure. The effect may be real or may be an artifact of the model assumptions; however, it is clear from the data that the rougher surfaces exhibit a flattening of the conductance vs. pressure at higher loads.

Additional comparisons of the modified Yovanovich model with data are shown in Section 4.

3. Description of experiments

A series of experiments was performed in the small test apparatus shown in Fig. 3. Table 1 summarizes the range of parameters explored in these experiments. The apparatus allows independent control of the important environmental conditions, in reactor-relevant regimes.

The contact conductance was measured for a number of steel and Be specimens having surface roughness from 0.5 μm to 5 μm. The roughness was produced by first cutting and polishing 1″-diameter disks 1/4″ thick, and then grit-blasting with various pressures and Al_2O_3 grit sizes from 25 to 150 μm. Example SEM photographs of the Be surfaces are shown in Fig. 4. Linear profilometry was performed on the surfaces, and the r.m.s. roughnesses computed. The Be shows a highly fractured morphology, whereas steel surface roughness usually exhibits much more ductile deformations. Typically, in measurements with a Be–steel interface, a polished ($\sigma < 0.1$ μm) steel surface was used.

Table 1
Range of parameters explored in experiments

Specimen materials		304 SS, Be (100% dense)
Surface roughness	δ	$0.5 \leqslant \delta \leqslant 5$ μm
Cover gas composition		N_2, He
Cover gas pressure	p	1 Torr $\leqslant p \leqslant$ 1 atm
Contact pressure	P_c	0–10 MPa
Heat flux	q	0–20 W cm^{-2}
Contact conductance	h	$200 \leqslant h \leqslant 20{,}000$ W m^{-2} K^{-2}

The background gas pressure was varied from 100 to 760 Torr of He. Pressures were measured with a mercury manometer. The contact pressure was varied from 0 to 10 MPa by use of a manually driven hydraulic ram press. The ram enters the vacuum chamber via a flexible bellows which transmits the force but maintains a tight vacuum seal. Loads were measured with a strain-gauge load cell.

The heat flux is controlled by varying the voltage to the heater. The heat source is a 500-W cable heater brazed to a copper block to distribute the heat. Heat flux measurements are made by the use of thermocouples located in "heat-flux meters" above and below the test specimens, and also located in the specimens themselves. The heat-flux meters consist of 1″-diameter rods of copper or other materials with known thermal conductivity and precisely located thermocouples inserted at regular intervals. Small heat losses between the heater and coolant are therefore not important. The coolant is water at 15 °C.

4. Experimental data and model comparison

Selected data are presented in this section and compared with the model described above, and with the original model of Yovanovich.

4.1. *Effect of gas pressure and contact pressure with non-conforming surfaces*

Fig. 5 shows data for Be treated with 25-μm Al_2O_3 grit, yielding an average surface roughness of 0.5 μm according to profilometry data. Data were collected for contact pressures of 0–7 MPa and He gas pressures of 100, 250 and 760 Torr. The heat flux in this case was maintained between 114 and 126 kW m^{-2}. Several data sets from different runs confirm reproducibility. Both

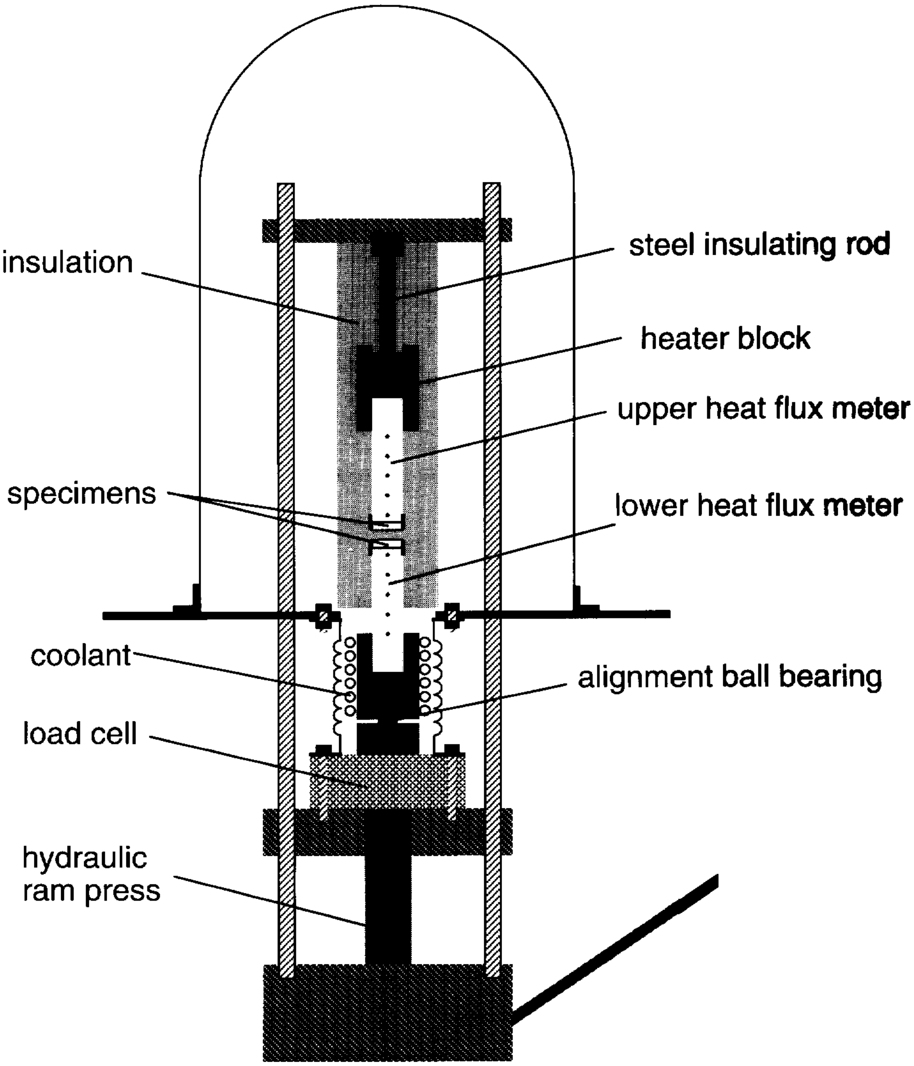

Fig. 3. Test apparatus used in the gap conductance experiments.

gas pressure and contact pressure are seen to have a large effect on the interface conductance. As the gas pressure is reduced, the gas conductance h_g diminishes. At 100 Torr, there is still sufficient gas pressure to provide 5000 W m^{-2} at near-zero contact pressure (h_c vanishes at $P_c \rightarrow 0$).

Fig. 6 shows data for higher-roughness Be, treated with 150-μm Al_2O_3 grit at higher impact velocity, yielding an average surface roughness of 3–5 μm. The surface exhibits localized "peaks" of 5–10 μm; the brittle nature of Be left the surface with structure dissimilar to random roughness, which is easier to obtain with ductile surfaces. Data are shown for contact pressures of 0–7 MPa and He gas pressures of 100 and 760 Torr. As above, the heat flux in this case was maintained between 114 and 126 kW m^{-2}. The base level of conductance is only slightly lower than for the smoother surface. However, the variation with contact pressure is substantially reduced at 1 atm He. At low gas pressure the conductances are very similar. The data show that surface roughness provides a kind of "compliance" that reduces the sensitivity of the conductance to external forces.

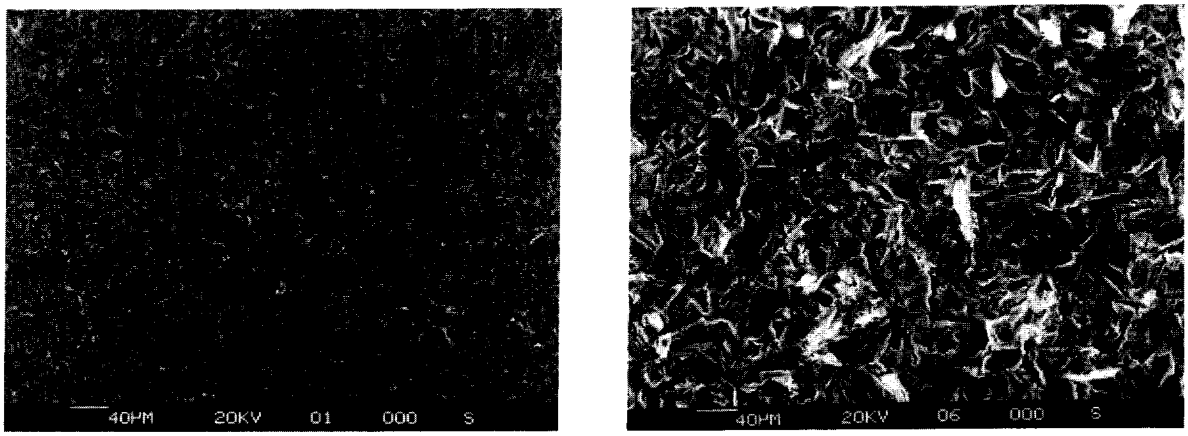

Fig. 4. SEM photographs of the Be specimen surfaces.

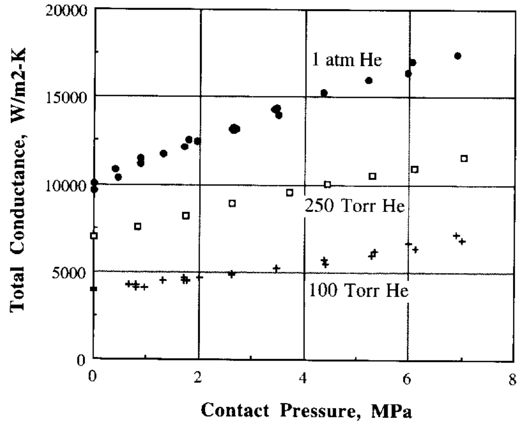

Fig. 5. Be-on-steel contact conductance for $\epsilon = 0.5$ μm.

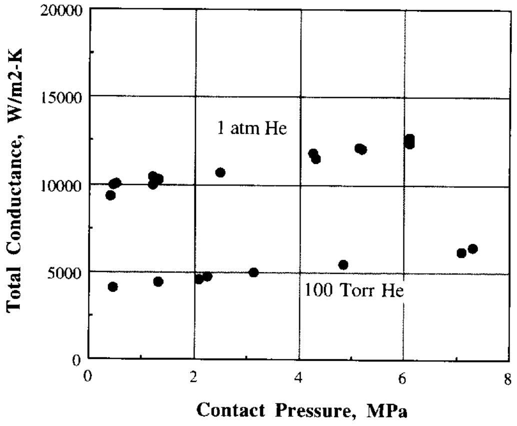

Fig. 6. Be-on-steel contact conductance for $\epsilon = 4$ μm.

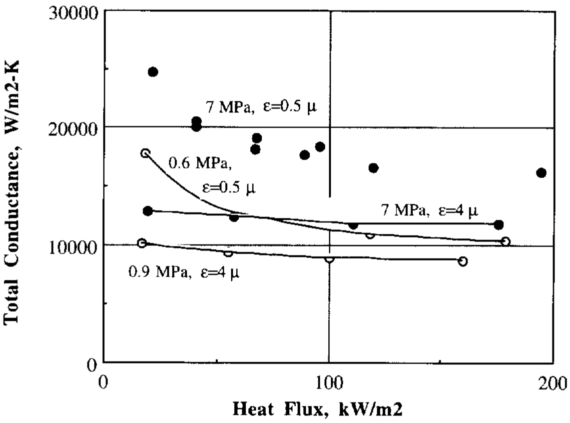

Fig. 7. Effect of thermal deformation on Be–steel contact conductance for $\epsilon = 0.5$ μm and $\epsilon = 4$ μm.

4.2. Effect of heat flux and thermal deformations

Fig. 7 shows the effect of varying the heat flux with the He gas pressure held fixed at 760 Torr. Two contact pressures were measured with the smoother Be specimen: 0.6 and 7.0 MPa (data near zero contact pressure are avoided due to the inherently unpredictable behavior of the contact conductance under this condition). In this case, a fairly strong degradation of conductance occurs at lower values of heat flux. Above about 100 kW m^{-2}, the dependence on heat flux diminishes. While the exact nature of this effect is unknown, it is clear from the model that h_c is not very strongly affected by deformations when contact pressure exists, and that its magnitude is too small to account for the changes. Further studies will be needed to elucidate this effect.

The interface conductance at 0.6 MPa contact pressure is lower than at 7 MPa, as expected. The transition to a conductance relatively independent of heat flux occurs at roughly the same heat flux, which suggests that the thermal deformation is a stronger effect than pressure deformations. Based on the analysis in Section 2, 100 kW m^{-2} should produce roughly the same amount of deformation as 7 MPa of contact pressure.

Measurements with the rougher Be surface are also shown in Fig. 7. The data suggest that the larger surface roughness produces such a large mean separation, even at $q = 0$, that the effect of thermal deformation is nearly absent. As with varying contact pressure, the rougher surfaces act as a compliant zone to mediate changes due to thermal deformations.

4.3. Comparison of models and data

Model predictions based on the modified conductance model and the original unmodified model are shown in Fig. 8, compared with data at 1 atm He. The model predictions are extremely sensitive to the assumed roughness. Much better agreement is found with the model assuming 5–10 μm of roughness. It is very likely that the two surfaces are not exactly flat, so that an effective roughness is seen in the data.

The tendency for the dependence on contact pressure to flatten out at higher load is clearly seen in both the data and the model prediction. The dependence on gas pressure is still evident. The predictions of the modified model are sometimes higher and sometimes lower than the original model for conforming surfaces. At low values of roughness, thermal deformation always degrades the heat transfer. However, a surprising prediction of the modified model is that thermal deformations in some cases *increases* the conductance. This is postulated to result from the increased conductance in the contacting areas, which may in some cases outweigh the decreased conductance in the non-contacting areas. Further studies will be needed to understand this effect fully.

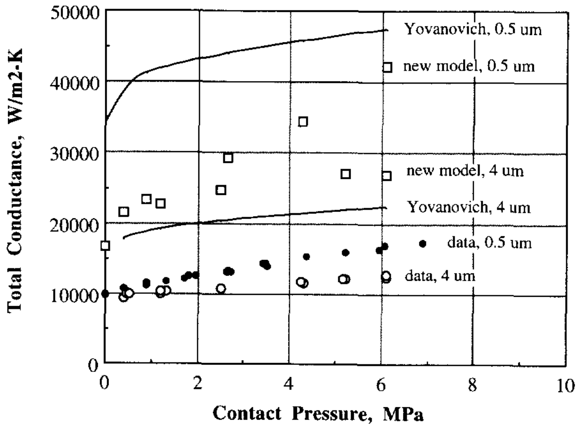

Fig. 8. Comparison of models and data.

5. Conclusions

Data for two values of surface roughness show that the contact conductance between solid metallic surfaces depends strongly on several parameters, including gas pressure, contact pressure and heat flux. Higher surface roughness leads to lower base-level conductance, but appears to significantly reduce the sensitivity to environmental changes. A new model was developed including the combined effects of thermal deformation and contact pressure on the thermal contact conductance. The model agrees generally with the data if the surface roughness is much larger than profilometry data predicts, suggesting that non-flatness makes an important contribution. Unexpected increases in conductance are predicted at lower values of heat flux and higher values of contact pressure. Further research will be required to refine the models and better understand these effects.

The moderating effect of surface roughness suggests that, for blankets employing Be in sintered block form, the use of roughened surfaces should be considered, to reduce the effect of thermal deformation and other changes in geometry induced by swelling and creep. Some minimum level of contact pressure is highly desirable, and designs should incorporate this if possible. Finally, the dependence of contact conductance on gas pressure suggests that an active control mechanism can be employed during operation to account for changes in power level or other changes which are detectable by diagnostic measurements. This capability may be especially useful in tests performed in test reactors such as ITER.

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