Contact Heat Transfer—The Last Decade

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Nomenclature

a = radius of contact spot, m
A = area, m^2
b = radius of heat flow channel, m
b_1 = radius of contour area, m
d = dimension defining specimen size, m
E = Young's modulus of elasticity, N/m^2
E' = effective elastic modulus,

$$= 2\left(\frac{1-\gamma_1^2}{E_1} + \frac{1-\gamma_2^2}{E_2}\right)^{-1}, \text{ N/m}^2$$

f = constriction alleviation factor
g = temperature-jump distance, m
h = thermal conductance, W/m^2-K
H = microhardness of softer material, N/m^2
k = harmonic mean of the thermal conductivities of the two solids in contact, W/m-K
m = moment of the power spectral density of the surface profile (units depend on the order of the moment)
n = number of contact spots
N = density of contact spots, $1/m^2$
P = contact pressure, N/m^2
q = heat flux, W/m^2
Q = heat flow, W
r = radial coordinate, m
R = resistance, $m^2 \cdot K/W$
S_u = ultimate strength of the softer material, N/m^2
t = thickness of surface film, m
T = temperature, K or °C
ΔT = temperature difference, K
W = total load on the surface, N
α = coefficient of linear thermal expansion, 1/K
δ = effective thickness of gas gap, m; also, separation between mean surface planes
λ = mean free path of gas molecules, m
ν = Poisson's ratio
ξ = waviness number, $= Wd/E'\sigma_1$
ρ = radius of curvature, m
σ = rms surface roughness, m
σ_1 = total rms surface roughness (dependent on σ and d), m

Subscripts

av = average
c = constriction
cd = disk constriction
f = surface film
g = gas
i = individual
n = nominal
T = total
1,2 = solids in contact

Introduction

THERMAL contact resistance is the resistance to heat flow offered by a joint because the area of actual contact is only a small fraction of the nominal area (Fig. 1). It is defined as the ratio of the temperature drop at the interface to the heat flux (Fig. 2),

$$R = \frac{\Delta T}{Q/A} \tag{1}$$

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The thermal contact conductance is then

$$h = \frac{Q/A}{\Delta T} \tag{2}$$

The conductance should be high for applications such as nuclear reactors, gas turbines, aircraft structural joints, surface temperature measurements by thermocouples, cooking on a hot plate, and the setting process during a total hip prosthesis.[1-8] When mechanically strong insulation is required, however, such as in the storage of cryogenic liquids, thermal isolation of spacecraft components, mechanically strong insulating cylinders for internal combustion engines, and thermal insulation of high-temperature batteries,[9-12] the contact resistance must be as high as possible.

The heat transfer across a joint may take place by conduction through the actual contact spots, conduction through the interstitial material, and radiation across the gaps. Since radiation is significant only at high temperatures, this mode of heat transfer is usually neglected. This paper, therefore, considers only the theoretical and experimental studies of conduction through the actual contact spots and through the interstitial material. Special problems introduced because of the geometry of contact, cycling of load, and heat flux are also discussed. The review is restricted to steady-state problems.

It must be pointed out that bibliographies and views exist that cover the work done in the field of contact heat transfer into the late 1960's.[13-21] The present paper deals primarily with more recent work, i.e., since 1970. Where reference has been made to an earlier work, it is with a view to developing a particular topic systematically.

Resistance of a Single Constriction

Since thermal resistance results from most of the heat being constrained to flow through actual contact spots, the first logical step in determining the contact resistance would be to estimate the resistance associated with a single contact spot. The constriction resistance of such a spot is a measure of the additional temperature drop due to the presence of the constriction. The shape of a constriction and associated boundary conditions depend upon the nature of the problem being considered.

Disk Constriction in Vacuum

The solutions to the constriction resistance problem date back to 1949.[22-27] Gibson[28] attempted a direct solution to the mixed boundary value problem at the interface. His approach is very similar to that of Hunter and Williams,[26] and his result can be expressed as

$$f = 1 - 409183(a/b) + 0.338010(a/b)^3 + 0.06792(a/b)^5 + \ldots \tag{3}$$

where f is the nondimensional constriction resistance (R_c/R_{cd}); R_c is the constriction resistance based on total heat flow, and $R_{cd} = 1/(4ak)$, the constriction resistance of a disk of radius a in a half-space. Note that f is always less than 1 and is sometimes called the "constriction alleviation factor." It may also be pointed out that Gibson's solution differs very little from Roess' approximate solution[22] derived in 1949.

Yovanovich[29] obtained solutions for the preceding problem after replacing the constant temperature boundary condition on the contact area by the condition that the heat flux over the contact area is proportional to $(1-(r/a)^2)\mu$. It may be noted that a similar approach was considered earlier by Roess[22] and Cooper et al.[25] Yovanovich developed relations for the nondimensional resistance almost identical to those developed by Cooper et al.[25]

Conical Constrictions

Since the asperities in contact can be considered to be cones of large semiangle (~80 deg), it is desirable to estimate the resistance offered to heat flow by a conical constriction. With such a model, it is a straightforward matter to include the effect of the fluid surrounding the constriction.

Theoretical and experimental studies of the thermal resistance of a conical frustum with a semiangle up to 80 deg in vacuum were studied by Williams,[30] who found that his theoretical predictions, in general, overestimated the thermal resistances. The difference was considered due to the contact areas being actually larger than those predicted using Meyer hardness.

The problem of conical constriction in vacuum was simulated in an electrolytic tank analog by Major and Williams.[31] The maximum value of the cone semiangle used in the experiments was 60 deg. The authors found that the resistance decreased as the cone semiangle increased.

A numerical and experimental analysis of the problem of conical constrictions has been considered by Madhusudana.[32] He considered cones of semiangles up to 85 deg surrounded by a vacuum or a conducting medium. He found that the presence of a conducting fluid significantly reduces the resistance, especially at the practically important low radius ratios. He also found that in a vacuum and for large values of the cone semiangle (≃85 deg), there is very little difference between conical and disk constriction resistance. Therefore, for nominally flat, rough surfaces, whose asperities have small slopes with respect to the contact plane, the disk constriction resistance values could be used with confidence.

Major[33] has also presented a finite difference analysis of the problem of conical constriction in vacuum, although the configuration used is slightly different. Results were obtained for values of the cone semiangle up to 68 deg.

Constrictions of Other Shapes

In some applications, the constriction to heat flow may be other than a circular area. These studies[34-41] are presented in Table 1 and deal primarily with constrictions on the boundary of a half-space. Therefore, caution must be exercised when applying the results of these studies to specific problems.

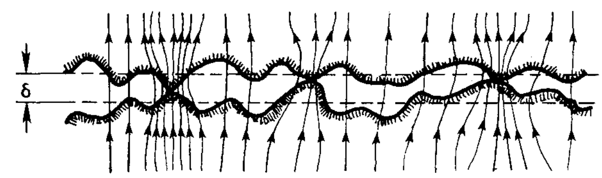

Fig. 1 Heat flow through a joint.

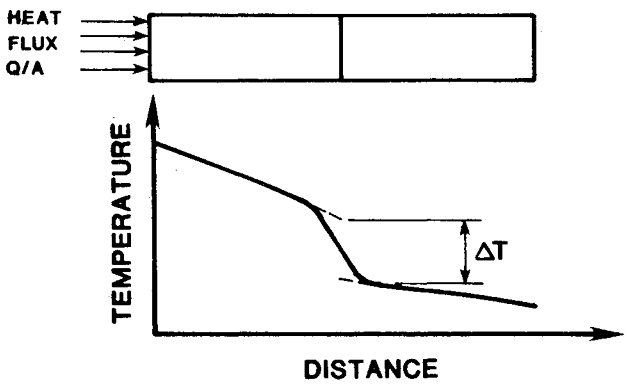

Fig. 2 Axial temperature distribution through a joint.

Table 1 Summary of studies dealing with constrictions on the boundary of a half-space

Author(s)	Types of constriction	Results
Veziroglu and Chandra[34]	Symmetrical two-dimensional and nonsymmetrical	Graphical
Veziroglu et al.[35]	Circular and rectangular	Graphical
Yovanovich[36]	Circular, rectangular, annular	Tabular form
Yovanovich and Schneider[37]	Circular annular	Closed form
Schneider[38]	Circular, rectangular, annular	Tabular form
Yovanovich et al.[39]	Annular, circular, rectangular, triangular	Correlations and tabular form
Yovanovich et al.[40]	Circular, square, astroidal	Tabular
Yovanovich and Burde[41]	Triangular, semicircular, L-shaped	Correlations

Thermal Resistance of Multiple Contact Spots in Vacuum

If R_i is the resistance associated with a single contact spot and the fluid surrounding it, the overall resistance of the joint of the heat flow is given by

$$\frac{1}{R_T} = \sum_{i=1}^{n} \frac{1}{R_i} \tag{4}$$

where n is the number of contact spots in the joints.

In terms of conductances, one could write

$$h_T = \sum_{i=1}^{n} h_i \tag{5}$$

Since each side of a constriction has a resistance equal to $f_i/(4ak)$, the resistance of a contact spot in vacuum is $f_i/(2ak)$. If the contact is between two different solids, then k would be the harmonic mean of the two conductivities. Thus, for joints in vacuum,

$$R = \sum_{i=1}^{n} \frac{f_i}{(2a_i k)} \tag{6}$$

and

$$h = \sum_{i-1}^{n} \frac{(2a_i k)}{f_i} \tag{7}$$

If $\bar{\alpha}$ is the average radius of the contact spot and the variation in the constriction alleviation factor f is neglected, then

$$R = f/2n\bar{a}k \tag{8}$$

$$h = 2n\bar{a}k/f \tag{9}$$

Thus the problem reduces to one of determining n and a. Now n and a both depend on δ, the separation between planes that defines the mean height of surface profiles (Fig. 1). Also, n depends on the profile height distribution, while $\bar{\alpha}$ may be expected to depend on the profile slope distribution. Thus, both deformation and surface analyses would be required in estimating the contact conductance.

First, it is necessary to know whether the deformation of the asperities is elastic or plastic. Greenwood[42] had shown that, unless the surfaces were carefully polished, the deformation would be plastic even at the lightest loads. His analysis was based on asperities of spherical shape.

Mikic[43] suggested the use of an index

$$\gamma = H/(E' \,|\tan\theta|) \tag{10}$$

where H is the microhardness of the softer material, E' the effective elastic modulus, and $\tan\theta$ the mean absolute slope of the surface profiles. According to Mikic, the deformation is predominately plastic for $\gamma < 0.33$ (for most surfaces $\gamma < 0.1$).

Based on statistical geometry theory, Bush and Gibson[44] defined a new plasticity index that depends on m_0, m_2, and m_4 (the first three moments of the power spectral density of the surface profile), as well as on E and H. The asperities are expected to deform plastically if $\psi > 2$. It may be noted that m_0 and m_2 are, in fact, related to the standard deviation of profile height (i.e., the surface roughness, σ) and $\tan\theta$, respectively.

It is clear from the preceding discussion that the statistical nature of surface profiles controls not only the number and size of contact spots, but the mode of deformation as well. The statistical nature of contact conductance was demonstrated experimentally by Veziroglu,[45] who found variations of up to $\pm 60\%$ in the measured value of conductance of 15 pairs of apparently similarly finished surfaces.

Nominally Flat Rough Surfaces

If the average contact spot radius is assumed to be a constant, then the number of contact spots and, therefore, the conductance, are directly proportional to the actual contact area, A_{act}. Popov[46] empirically determined that

$$A_{act} = A_{nom}(PB/E)^{0.8} \tag{11}$$

where A_{nom} is the nominal contact area, P the contact pressure, and B a function depending upon the sum of the average heights of asperities of the two surfaces in contact. Thus, according to Popov, the conductance is proportional to $P^{0.8}$. No mathematical expression for B was given in Popov's paper.

Novikov[47,48] derived the relationship between the thermal resistance and the load by performing a statistical analysis assuming spherical asperities whose heights obeyed a Gaussian distribution. He used Cetinkale and Fishenden's[23] expression for constriction resistance. For elastic deformations at low loads, the resistance was found to vary exponentially with the separation (and, therefore, the load) between the surfaces; at larger loads, the variation was found to be linear. For elastic-plastic contacts, the ratio of the number of plastically deformed contact spots to their total number was taken to be $\exp(-b^*/\sigma)$, where b^* is the critical deformation at which the projections begin to deform plastically.

In the statistical analysis of Tsukizoe and Hisakado,[49,50] it was assumed that the asperities were conical in shape, with normally distributed heights. The thermal resistance could then be expressed as a function of the dimensionless separation between the surfaces. Separation is a function of the applied load and, thus, a relationship between the thermal resistance and the load is established. The deformations were assumed to be plastic under a constant flow pressure. A noteworthy feature of this work is that a tentative correlation was proposed between the profile slope and the maximum height of asperities which took into account different types of surface finish.

Mikic's[43] analysis considered the Gaussian distribution of profile heights and slopes and the constriction alleviation factor given by Cooper et al.[51] Whether the deformation was plastic or elastic, Mikic found that the conductance was proportional to $P^{0.94}$. He also developed a theory for the increase in conductance, including the elastic deformation of the substrate.

Sayles and Thomas[52] considered elastic deformation of rough Gaussian surfaces and found that the number of contacts was proportional to load, while the mean contact spot size was almost independent of load. This resulted in the conductance being nearly proportional to the load and the mean slope, confirming Mikic's results. Sayles and Thomas also discussed how their method could be extended to anisotropic surfaces. No constriction alleviation factor was used in their analysis.

As mentioned earlier in this section, Bush and Gibson[44] considered statistical geometry theory to evaluate the conductance. The constriction alleviation factor used was that of Gibson.[28] Like Mikic, they found that whether the contacts were plastic or elastic, the thermal contact conductance was proportional to $P^{0.94}$. In view of the asperity interactions, the theory is not applicable for large loads.

The preceding discussion of nominally flat rough surfaces in a vacuum reveals that

1) whether the contact is elastic or plastic, the thermal conductance varies nearly linearly with the load; and 2) the thermal conductance is proportional to mean absolute slope of surface profiles. The first of these conclusions implies that the average contact spot size remains substantially constant with the load. If the number of contact spots remained constant however, the conductance would be proportional to the $(\text{load})^{0.5}$.

Effects of Large-Scale Surface Irregularities

Most practical surfaces contain, in addition to roughness, large-scale errors of form such as waviness and deviation from flatness. These departures from an ideal flat surface will also affect the thermal resistance.

If two rough spherical surfaces (or the crests of two wavy and rough surfaces) are in contact, the configuration can be considered to be as shown in Fig. 3. The contact geometry would be similar if one of the surfaces were flat. In these cases, the resistance is obtained by adding the constriction resistance of the "contour" area of radius b to the constriction resistance of the multiple contact spots distributed within the contour area.[53]

In most of the work carried out before 1970, the size and distribution of the contact spots were assumed to be known. Actually, these have to be determined as functions of the mechanical loading, surface characteristics, and mechanical properties of the contacting solids. It is usually assumed that the roughness heights deform plastically while the large-scale irregularities deform elastically. The work of McMillian and Mikic[54] was based on the above considerations. One of the unexpected conclusions from their work was that the conductance of wavy surfaces can be increased by making the surfaces rough, thereby increasing the contour area.

Hsieh et al.[55] approximated the contact of two rough wavy surfaces by a model consisting of a smooth spherical surface in contact with a flat rough surface. The roughness asperities were assumed to be conical in shape and normally distributed. The results showed that conductance is strongly dependent on surface roughness, and the resistance of the macroscopic constriction, due to waviness, can be neglected. This conclusion is contrary to that of Clausing and Chao,[56] whose experimental work suggested that the microscopic constriction is of secondary importance for many surfaces. Yovanovich[57] considered the contour area to be a very long spiral when a soft turned surface is in contact with a harder, smooth flat surface. At relatively high loads ($P/H<0.05$), the contact would be continuous along the spiral whose resistance alone would be the thermal resistance. At moderate and low loads ($P/H<0.03$), however, a contribution due to roughness must be added.

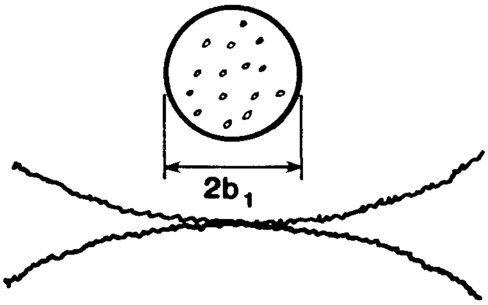

Fig. 3 Contact of two spherically convex surfaces.

All of the work discussed thus far considered the total resistance to be the sum of the resistance due to roughness and the resistance due to waviness or flatness deviation. A different approach was adopted by Popov and Yanin,[58] who considered the total resistance to be given by

$$R = R_r(A_n/A_c) \tag{12}$$

in which R_r is the resistance due to roughness, A_n the nominal area, and A_c the contour area. The contour areas were determined assuming elastic deformation of the waves. For spherical waves, the contour area was found to be proportional to $P^{2/3}$, whereas for cylindrical waves, the contour area varied as $P^{1/2}$. The experiments cleary demonstrated that the resistance increased when waviness or flatness deviation was present. It was also noted that the resistance for a spherical surface was larger than the resistance for a corresponding cylindrical surface. However, it must be pointed out that all of the tests were conducted in air and, therefore, the resistance and its variation would be affected by the effective gap thickness.

A vertical section through a surface can be considered to contain a continuous spectrum of wavelengths extending down to atomic dimensions. Therefore, Thomas and Sayles[59] argued that waviness and roughness should be discussed in terms of the bandwidths of the spectrum rather than of fixed wavelengths. They found that the dimensionless contour radius b_1/b was given by

$$b_1/b = 0.44\xi^{1/3} \tag{13}$$

where $\xi = WE'/\sigma_1 d$, the "waviness number"; W is the total load on the surface; and σ_1 the "total" rms roughness.

It was found that the effect of waviness could be neglected if $\xi > 1$. Since in all practical situations $\xi < 1$, the authors concluded that the waviness effect should never be neglected.

Dundurs and Panek[60] solved the elasticity and heat conduction equations simultaneously so that the contact area could be expressed as a function of both the applied pressure and the heat flux. They considered a two-dimensional wavy surface, completely ignoring the roughness and the statistical nature of the waviness. They found that, due to heat transmission, perfectly flat surfaces might become wavy.

The experiments of Edmonds et al.[61] also confirmed that, at low pressures, the effect of waviness predominates; this is indicated by a lower value ($\sim 2/3$) for the load exponent. At higher loads, the waviness undulations would have been mostly flattened and microconstriction due to roughness would become more important.

Correlations for Thermal Contact Conductance in a Vacuum

Several correlations between the conductance and the parameters affecting it have been developed over the past 20 years. However, in keeping with the constraints of the present paper, attention will be focused on the more recent ones.

A least-squares analysis of some 92 experimental data points led Mal'kov[62] to the following correlation:

$$h\bar{a}/k = 0.118\ (PK_1/3S_u)^{0.66} \tag{14}$$

where S_u is the ultimate strength of the softer material and K_1 a constant depending on the average of the surface roughness heights. Apart from the use of $3S_u$ for the hardness, the major difference between this and the correlations proposed earlier by different authors is the rather low value (0.66) of the exponent.

Fletcher and Gyorog,[63] in their correlation for similar metals in contact, considered the following additional factors: 1) the mean junction temperature, 2) a gap dimension parameter accounting for the roughness as well as the flatness deviation, and 3) the variation of the above parameter with contact presure. They also made use of the Young's modulus E, rather than the microhardness, to nondimensionalize the pressure. The correlation fitted some 400 data points, representing the work of seven investigators, with an error of less than 24%.

The dimensional analysis of Thomas and Probert[64] considered that the nominal contact area did not play an important role in the variation of the conductance and therefore the total load, rather than the interface pressure, was taken to be one of the variables. Their analysis yielded two dimensionless groups, $C^* = C/(\sigma\kappa)$ and $W^* = W/\sigma^2 H$, where C is the total conductance of the contact. The data for stainless-steel/stainless-steel and aluminum/aluminum surfaces fell into two distinct groups, indicating that the dimensional analysis was incomplete.

The data for aluminum in the preceding work were combined with other data by O'Callaghan and Probert,[65] resulting in a total of 344 points, which followed the correlation

$$C^* = 3.73\ (W^*)^{0.66} \tag{15}$$

However, when the stainless-steel data were also added, the scatter increased.

The experimental results of Al-Astrabadi et al.[66] were also found to belong to the correlation for stainless-steel surfaces proposed by Thomas and Probert.[64] The experiments of Edmonds et al.[67] on the contact of optically flat copper surfaces with stainless-steel surfaces of various degrees of surface finish, on the whole, obeyed the relationship

$$C^* = 0.26\ (W^*)^{0.96} \tag{16}$$

However, when the data were grouped into two regions according to their roughnesses, the load term exponents were 0.60 and 0.61 for high and low roughness regions, respectively, indicating that both roughness and waviness contributed to the resistance.

Popov[68] proposed a correlation similar to that of Mal'kov,[62] except that the analysis was restricted to nominally flat rough surfaces. The pressure term exponent was found to be 0.956—the higher value indicating the absence of waviness.

Theoretical correlations assuming Gaussian distribution of asperity weights and elastic deformation of asperities were proposed by Blahey et al.[69] Their analysis showed that the pressure term exponent had a range of 0.93-0.95, depending on the asperity tip radius and surface roughness.

Effect of Surface Films

The existence of a surface film may be either intentional, as in electroplated surfaces, or unavoidable, as in oxidized surfaces. A comprehensive review of the literature, covering the work until the late 1960's on the effect of oxide films on thermal resistance, has been presented by Gale.[70] A generally accepted conclusion is that oxide films, unless sufficiently thick, do not appreciably increase the resistance although they may have a major effect in electrical contact resistance. Assuming one-dimensional flow through the film and no interaction between the solid spot and film resistances, Gale obtained the following approximate expression for the resistance of a single spot:

$$R = (\tfrac{1}{4}ak) + (t/\pi a^2 k_f) \tag{17}$$

where t is the thickness of the film and k_f its conductivity. Based on this equation, a constriction magnification factor C_m was defined as

$$C_m = 1 + (4tk/\pi a k_f) \tag{18}$$

which shows that the increase in resistance is proportional to the ratio of the thickness of film to contact spot radius and the ratio of the conductivity of the parent metal to that of the oxide film. The oxide film contributes to the total resistance for contacts having radii less than 10.

The experiments of Tsao and Heimburg[71] on aluminum 7075-T6 surfaces in dry air showed expected trends, namely, that the time of exposure increased the resistance, while degassing of the surfaces decreased resistance. However, exactly opposite trends were noted for the specimens aged in laboratory (humid) air. This anomalous behavior was thought to be due to the decrease of fracture stress of the aluminum oxide films in the presence of absorbed gases, especially moisture.

The analytic solution of Mikic and Carnascialli[72] is based on the premise that, for a fixed geometry, any increase in the thermal conductivity in the vicinity of contact points should reduce the value of the resistance. Their results showed that the increase in conductance due to plating is directly dependent on t/a and k_p/k, where k_p is the conductivity of the plating material. For wavy surfaces in contact, the contour area radius is so large that the plating must be very thick to achieve any significant reduction in resistance.

Based on experimental measurements, Tsukizoe and Hisakado[49,50] estimated that, for copper surfaces covered with oxide films, the ratio of the thermally conducting area to the apparent area of contact was larger than the corresponding ratio for the electrically conducting area. This again confirms that electrically insulating surface films may be thermally conducting since they permit a flow of phonons even though the motion of electrons is inhibited. It was also suggested that, for smooth surfaces, the slope of asperities is small and, therefore, the oxide films are less likely to break down. Thus, if the oxide films are present, the smoother surfaces may have higher resistance.

The theoretical work of Kharitonov et al.[73] considered the effects of both oxide films and coatings of higher conductivity metals, and led to the following conclusions:

1) For flat rough surfaces, the coating of a few-tens-of-microns thick will noticeably reduce the thermal contact resistance.

2) For wavy surfaces the contour radius might have a value of a fraction of 1 mm, and the coating thickness mentioned in point 1 would be ineffective.

3) Since the oxide layers usually have thicknesses of 1 μm and their conductivity is smaller than that of metals by factors of 3-30, the resistance depends only weakly on the oxide layer.

It may be added that the last conclusion may not be quite valid in view of the findings of Gale[70] previously mentioned.

Yip,[74] considering Gaussian surfaces and assuming uniform thickness of oxide films, demonstrated that the oxide films can cause a drastic increase in the resistance. His experiments on three pairs of aluminum alloy (6061-T6) surfaces clearly demonstrated that the effect of oxide film is more pronounced for smoother surfaces.

The results of previous investigators were confirmed in the experiments of Mian et al.[75] on steel-steel (EN3B) surfaces in a vacuum. They also found that the initial thickness of the oxide caused a considerable rise in the resistance, but additional thicknesses of oxide led to smaller increments of resistance.

Effect of Interstitial Materials

Whereas the solid spot constriction resistance is in series with the surface film, it is in parallel with the resistance of the interstitial material. In the following discussion, the interstitial media is broadly classified as gaseous and nongaseous.

Heat Flow Through the Interstitial Gaseous Medium

Since the heat transfer across the gas filling the voids between the contacting surfaces is principally by conduction, then

$$h_g = k_g/\delta \tag{19}$$

where h_g is the heat-transfer coefficient for the gas gap, k_g the thermal conductivity of the gas, and δ the effective thickness of the gas gap.

For normal engineering surfaces in contact, the effective gap thickness would be similar in magnitude to the mean free path of the gas molecules. Under these conditions the "temperature-jump" effect becomes important (see Fig. 4), so that Eq. (20) is modified to

$$h_g = k_g/(\delta + g_1 + g_2) \tag{20}$$

Thus, the problem of determining the gap thermal conductance for a given gas (or gas mixture) reduces to one of determining the effective gap width and the temperature-jump distances.

Some investigators (for example, Cohen et al.[76]) had observed that the conductance between the fuel and the jacket in a nuclear reactor was independent of the gas composition. Kharitonov et al.[77] offered an explanation based on the fact that the accommodation coefficient α depends on the molecular mass of the gas. Thus, for helium with a low molecular mass, the accommodation coefficient will also be small. In such a case, the temperature-jump distance is approximately given by

$$g = \lambda/\alpha \tag{21}$$

where λ is the mean free path of the gas molecules.

Now, if λ is large compared to δ, Eq. (21) may be written

$$h_g \simeq k_g/g \simeq k_g \alpha/\lambda \tag{22}$$

Thus, although the conductivity of helium is very high, its accommodation coefficient is low, and, by Eq. (22), the gas conductance is only weakly dependent on the nature of the gas. For example, for pure surfaces of heavy metals, the gas conductance of xenon can be shown to be greater than that of helium although the conductivity of helium is 30 times that of xenon.

The experimental work of Madhusudana[78] indicated that the gas conductance increased with contact pressure due to the reduction in gap thickness with load. It was also found that, at any given contact pressure, the reduction in fluid conduction contribution was noticeable only at absolute pressures below 100 Torr (13 kPa).

The following expression for the gas gap conductance was proposed by Popov and Krasnoborod'ko.[79]

$$h_g = k_g Y_1/[(h_{\max 1} + h_{\max 2})(1-\epsilon)] \tag{23}$$

where $h_{\max 1}$ and $h_{\max 2}$ are the maximum heights of roughness for surfaces 1 and 2, respectively; ϵ is the approach of surfaces under load; and Y_1 is a function of $(1-\epsilon)$, the maximum thickness of the gas layer and the temperature-jump distances.

The temperature-jump distance g_m for a mixture of gases was determined by Vickerman and Harris[80] to be

$$g_m = \Sigma(x_i g_i/m_i^{1/2})/\Sigma(x_i/m_i^{1/2}) \tag{24}$$

where g_i is the temperature-jump distance of constituent gas i, x_i the mass fraction of constituent gas i, and m_i the molecular mass of constituent gas i. Their results for He-N_2 and He-Ar mixtures showed fair agreement with the data available in the literature.

The theoretical expressions such as Eq. (20) predict first an increase and then a decrease of gas conductance with temperature. However, the experiments of Garnier and Begej[81] indicated a continual increase of gas conductance with temperature, especially when the gap widths were comparatively small. The authors considered this to be due to the presence of free molecular conduction. Yovanovich et al.[82,83] have proposed correlations for the estimation of gas gap conductance. The correlations are somewhat similar to that of Dutkiewicz.[84]

A comprehensive review summarizing the current state of knowledge on gas gap conductance has been presented by Madhusudana and Fletcher.[85]

Effect of Nongaseous Interstitial Materials

The interstices may be filled with materials with a view to either decreasing or increasing resistance, thus providing a means for thermal control. Furthermore, a joint with a filler material is less sensitive to loads and surface conditions and thus offers the advantage of predictability of heat-transfer behavior. The interstitial materials may be metal foils, wire screens, greases, powders, or insulating sheets, depending on the application.

The use of interstitial materials as a means of thermal control, especially in spacecraft systems, has been discussed by Fletcher and co-workers.[86-92] These works also contain reviews of previous experimental work on low- and high-conductance filler materials. To classify various interstitial material/base metal combinations, Fletcher[13] proposed the use of a nondimensional conductance η,

$$\eta = (h_c t)_f/(h_c \delta_0)_b \tag{25}$$

where h_c is the contact conductance, t the thickness of filler material, δ_0 the equivalent gap thickness, f the junction with filler material, and b the base metallic junction.

It was observed that combinations for which $1 \leq \eta \leq 10$ (e.g., carbon fiber paper) offer excellent thermal isolation qualities and light weight. But, if strength is also required, then the use of medium mesh screen wire of low thermal conductivity material was recommended. Thermal control materials, for which $100 \leq \eta \leq 1000$, enhance contact heat transfer. Indium foil and filled silicon grease appeared to be the most suitable materials in this category, although grease may not provide a good environmental seal.

Feldman et al.[93] investigated the thermal conductance of selected thermal joint compounds to ascertain their thermal conductivity, weight loss, and resistance to hardening. Results indicated that silicon base thermal joint compounds had reasonable thermal conductivity and moderate weight loss over the range of test conditions.

A theoretical model for the prediction of the conductance of a screen wire contacting two solids was proposed by Cividino et al.[94] The model assumed elastic deformation of smooth clean wires and equal loading of all modes. Probably because of these and other simplifying assumptions, the theory consistently overestimated the conductance when compared with measured values.

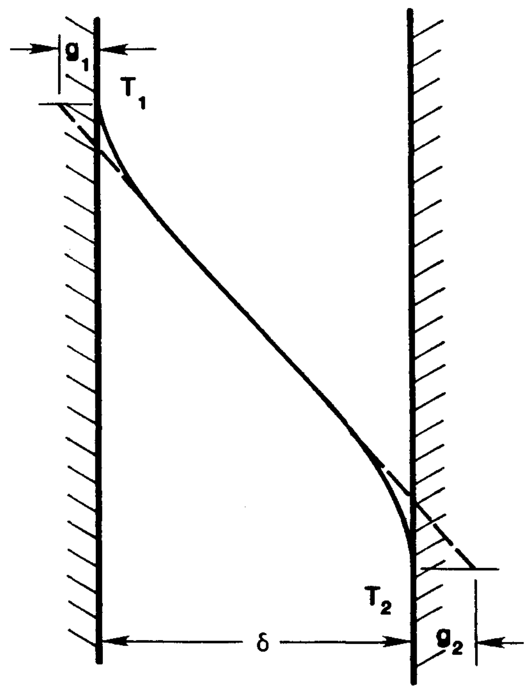

Fig. 4 Temperature-jump distance.

The experimental results of O'Callaghan et al.[95] indicated that the presence of a copper wire gauze between stainless-steel surfaces increased the conductance in a vacuum but decreased it in air. Further work by Al-Astrabadi et al.[96] showed that macroscopic constriction effects, due to either thermal distortion or badly mating surfaces, can be reduced or even eliminated by the insertion of such gauzes. They also noted that the method of weaving the screen wires results in the weft being a series of almost straight wires all in one plane with the warp interlaced. Therefore, contact occurs only between the warp and the solid surfaces, i.e., only at every other wire crossing. Another reason why Cividino et al.[94] overestimated the conductance is that they assumed contact to occur at every crossing instead of every other crossing.

Sauer et al.[97] found that with screens the conductance increased with increasing mesh size and the corresponding increase in the number of contacting regions. In another experimental work, Sauer et al.[98] found that films of lithium, graphite, silicon, and molykote lubricants improved the conductance of stainless-steel joints; such improvements being more noticeable (eight- to seventyfold) in a vacuum than in air (zero- to sixfold).

Effect of Heat Flow Direction

Some investigators[99,100] observed that the conductance is sensitive to direction of heat flow, especially if the joint is made up of dissimilar materials. This phenomenon, which may be called thermal rectification, could have applications in thermal control of systems; that is, suitable material combinations could be used as thermal switches.

Since the solid-state theory of Moon and Keeler[101] cannot explain the rectification behavior observed in joints of similar materials, it is now generally accepted that thermal rectification is caused by the distortion of the contact surface due to local temperature gradients.

The experimental studies of Williams[102] indicated, among other things, that the contact elements do not have to be dissimilar to exhibit rectification, and that the rectification effect decreases rapidly as the number of reversals increases. His experiments on a pair of Nilo 36 (an alloy of low thermal expansion) specimens revealed no effect on direction, confirming that the thermal distortion of contacting surfaces is necessary for rectification.

Veziroglu and Chandra[103] noted that the temperature gradients in the two specimens, causing differential radial expansions, result in the change of curvatures of the contacting surfaces. This theory, however, cannot explain the direction effect observed for similar materials.

A different approach to the problem was proposed by Barber,[104] who found the steady-state temperature distribution in two semi-infinite solids with spherical surfaces in contact, assuming no heat flow across the interface except through the circular contact area. This temperature distribution causes thermal strains through which one can find the load that must be applied to the solids to establish a contact area of the assumed size. Thus, the contact resistance, which depends on the contact area, was expressed as a function of the load as well as the heat flux (and its direction). Elastic deformation was assumed. Again, Barber's theory cannot explain the rectification behavior observed with similar materials.

Thomas and Probert,[105] in their experiments on stainless-steel/stainless-steel contacts, observed a large direction effect when one of the surfaces was bead-blasted and the other lapped; the conductance was higher when the heat flowed from the rougher to the smoother surface. When both surfaces were rough (bead-blasted), however, the rectification effect was not as significant. According to the models of Veziroglu and Chandra[103] or Clausing,[106] the conductance for heat flow in the SS→Al direction must be greater. Thomas and Probert concluded that the geometrical theories could not explain their results. Also, contrary to William's observations,[102] they noted that the directional effect increased with the number of reversals.

Using the principle of rectification, O'Callaghan et al.[107] constructed a thermal rectifier consisting of a multilayer stack of thin disks, each disk having one surface roughened, the other surface smoother, and so arranged that all of the rough surfaces were pointing in the same direction. For the stack consisting of brass disks, the conductance was higher when heat flowed from a rough to a smooth surface, while the opposite was true for stainless-steel stacks.

Further experiments of O'Callaghan and Probert[108] indicated that all contacts between dissimilar materials or dissimilar surfaces of the same material exhibited rectification with the exception of the contact between Fluorosint (reinforced PTFE) and Invar. Repeated thermal cycling reduced the direction effect to zero, endorsing the observation of Williams.[102]

Jones et al.[109,110] observed that, in the absence of radial heat losses, a constant axial temperature gradient causes the flat sections to bow with a radius of curvature, with the hotter end of each specimen becoming convex and the colder end concave. Thus if heat flows from material 1 to 2, where $\alpha_1/k_1>\alpha_2/k_2$, the contact would be peripheral, whereas for flow direction 2→1, the contact would be central (Fig. 5). The experiments on stainless-steel/aluminum contacts in a vacuum confirmed the theory. It may be noted that the constriction of heat flow toward a central contact is greater than the constriction when the heat flow is peripheral. Therefore, the conductance for the SS→Al direction must be higher. This is in contrast to the results observed by previous investigators of flat contacts.[99,100,108,111]

The experiments of Al-Astrabadi et al.[112] indicated that the conductance values were always higher for the heat flow in the SS→Cu direction irrespective of whether one surface was initially flat and the other surface convex. Thus, their results for flat contacts again disagree with those of previous workers. A possible reason is that, the surfaces being optically flat, the microscopic resistance would be small compared to the macroscopic resistance. Also in Refs. 109, 110, and 112, the order in which the joints were tested is not specified. This factor could be important in the rectification behavior of dissimilar materials.[102] Their results for convex/flat surfaces, however, follow expected trends, since the resistance

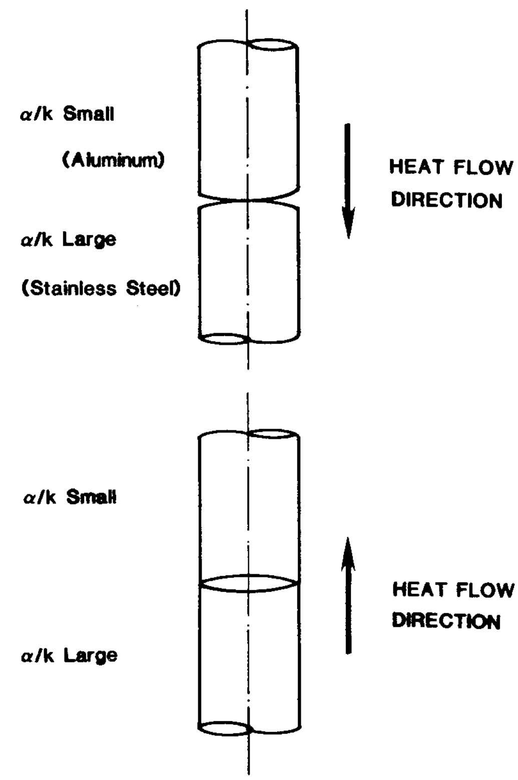

Fig. 5 Distortion of initially flat surfaces due to heat flow.[109,110]

in this case is obviously due to macroscopic constriction. Al-Astrabadi et al.[112] also observed that for stainless-steel (convex)/copper (optically flat) surfaces in contact, the conductance increased by a factor of 68 as the heat flux in the SS→Cu direction increased from 0 to 30 kW/m^2. This was due to a decrease in the disk-type constriction. For heat flow in the Cu→SS direction, the opposite was true, although the decrease in the conductance was only slight.

The theoretical study of Dundurs and Panek,[60] discussed earlier, also indicated that the conductance is higher for heat flowing from the material with the higher "distortivity." Thus, for example, the conductance for the SS→Cu direction would be higher than for the opposite direction. This is in agreement with the results of previous investigators of macroscopic contacts, except those of Thomas and Probert.[105]

The surfaces used by Somers et al.[113] in their experiments on conductance of dissimilar materials had substantial flatness deviations. Their results, therefore, confirmed the macroscopic theory, with the conductance for heat flow from the material of higher α/k being the greater in all cases except zircaloy/aluminum, for which no directional effect could be found.

A novel thermal rectifier making use of a stack of stainless-steel disks and an aluminum bar expansion element has been described by Jones et al.[114] In this device, the differences in resistance due to heat flow direction were on the order of 35-50%.

The preceding discussion shows that the following conclusions may be made regarding the thermal rectification effect, although some anomalies still remain.

1) For surfaces that are initially convex, the conductance is higher when the heat flows from the material with the higher α/k ratio. This conclusion is also generally true for flat-smooth surfaces.

2) For flat-rough surfaces, the conductance is higher when the heat flows from the material with the lower α/k ratio.

3) Similar materials with dissimilar surfaces may exhibit the rectification effect.

4) At present, no satisfactory theory exists to explain the rectification behavior observed for similar materials in contact.

5) The rectification effect decreases as the number of reversals increases; however, results opposite to this conclusion have been observed.

Some Special Topics in Contact Heat Transfer

Stacks of Laminations

Heat transfer takes place through stacks of thin laminations in electrical machinery such as transformers and generators. Such stacks have also been used as strong insulating structures for cryogenic tanks and in thermal isolation systems for spacecraft.[115]

The theoretical work of Williams[116] indicated that the effective thermal conductivity of a typical turbogenerator core when immersed in hydrogen would be about three times the value in normal atmospheric air. Williams' experiments[117] on stacks of steel laminations in different atmospheres showed that, for tests in air, the solid spot conductance was predominant. As the conductivity of the interface fluid was increased, however, the fluid conductance contribution became progressively more significant, and with helium as the interstitial fluid, the proportion of the solid spot conductance was quite negligible.

O'Callaghan et al.,[4] in their experiments on grain-orientated silicon-steel and nonorientated electric-steel laminations, found that the resistance per lamination-to-lamination was independent of the number of laminations. The resistance initially decreased with load, presumably due to the pressing out of any slight buckle present in the laminations, but it reached an asymptotic value at a contact pressure of about 1 kPa. At pressures up to this value, there was no electrical breakdown of the insulating surface films. Therefore, to reduce the equilibrium temperatures and, hence, increase the thermal efficiency, the authors recommended that the transformer lamination cores be prestressed to 1 kPa.

The theoretical work of Veziroglu et al.[35] considered the heat flow channel to be finite, a necessary requirement when the contacts are between thin sheets. The predicted conductances were consistently higher than the experimentally measured conductances of Williams.[117] A possible reason for the discrepancy is that the theoretical analysis considered bare steel sheets, whereas the experiments were performed on enameled sheets. The experimental results of Veziroglu et al.[35] on stainless-steel stacks in air, however, showed good agreement with their theory. A definite hysteresis behavior was observed for this stack of laminations, with the conductance values during unloading larger than the corresponding values during loading.

The experimental work of Sheffield et al.[118] on stacks of electrically insulated sheets in a vacuum resulted in a simple correlation

$$k^* = 1.24\sqrt{P^*} \quad (26)$$

where $k^* = k_{\text{eff}}/k_s$; k_{eff} is the effective thermal conductivity of the stack and $P^* = P/H$.

Contrary to the observation of O'Callaghan et al.,[4] the conductance was found to increase continuously throughout the loading (10-45 MPa).

Al-Astrabadi et al.[119] proposed the following correlation for the conductance of stacks of thin layers in vacuum:

$$h^* = 3.025(P^*)^{0.58} \quad (27)$$

where $h^* = h_{11}t/k_s$; h_{11} is the thermal conductance from layer to layer; and t the thickness of an individual layer.

The correlation was based on the results of 18 experiments obtained in 6 separate investigations and was deemed to be successful since the scatter band was relatively narrow.

Hysteresis

The hyteresis effect refers to the experimental observation that, when a joint is subjected to cyclic loading, the conductance values during unloading are usually higher than the corresponding values during the first loading. The work done prior to the period under review indicated the following as possible causes for hysteresis.

1) During first loading, the actual contact is formed by the elastoplastic deformation of asperities in contact, coupled with the elastic deformation of the underlying material. During unloading, the reduction of the contact area is due only to the elastic recovery of both the asperities and the bulk sublayers. Thus the formation of the contact area during loading is greater than the recovery during unloading for a given change in the load. This would result in the actual contact area and, therefore, the conductance being higher during unloading.

2) Cold welding occurs between perfectly clean surfaces immediately on the establishment of the metal-to-metal contact. This effect would be more significant for soft metals such as copper, rather than for harder materials such as tungsten. Since the spots where cold welding has taken place will remain in contact even when the load is removed, the contact area and therefore the conductance can be expected to be higher than the corresponding values during loading.

Since the hardness of metals decreases with the temperature and duration of stress (see, for example, Ref. 120), the conductance can also be expected to increase with the duration of the loading. Thus, the conductance values during subsequent unloading and reloading must be higher than those during first loading. This effort of contact duration, however, would be significant only at temperatures considerably higher than ambient temperatures.

McKenzie[121] observed that when the contact pressure was changed from 0.8 to 1.07 MPa, it took more than 50 h before equilibrium was restored. Therefore, he suggested that the hysteresis effects might have been caused by the unintentional use of nonsteady-state data.

In a theoretical study, Mikic[122] considered a Gaussian distribution of asperity heights and assumed that during first loading the asperities deformed plastically, while for a reduction and a subsequent increase (up to the maximum load achieved in the first loading) the asperities deformed elastically. This would result in the actual contact areas during unloading (and subsequent reloading) being greater than those during first loading. The analysis showed that the number of contact spots was also substantially higher in descending loading. As a result of both of these effects, the conductance would also be higher during unloading. It should be noted that Mikic's analysis applies to nominally flat, rough surfaces in a vacuum and does not consider the deformation of the bulk material.

In the experimental work of Madhusudana and Williams,[123] eight different pairs of surface combinations were tested. Hysteresis was observed in all cases, whether the materials were similar or dissimilar and whether the tests were conducted in a vacuum or in air. For specially prepared surface combinations, such as pyramids contacting flats, the hysteresis effect was more striking than for contacts between randomly rough flat surfaces. This was explained by the fact that, in the former case, all of the contact spots are nearly coplanar and break simultaneously on complete removal of loads; with the second type of surfaces, however, the contact spots will not be in the same place, and the area reduction on decreasing load takes place more gradually. It was also pointed out that the observed hysteresis effect was most probably not due to cold welding since the contacting surfaces were most likely contaminated.

Bolted Joints

Most contact heat-transfer studies assume that the contact pressure is uniform over the interface. However, the pressure distribution is nonuniform over the contact area formed between metal surfaces joined together by means of bolts, screws, or rivets. The usual contact heat-transfer theories, therefore, require some modification when applied to bolted joints.

Whitehurst and Durbin[124] considered the analytical solution for a bolted joint to be very complicated and, therefore, suggested an experimental method called the "effective fin method." Basically, this method would involve the measurement of temperature gradients on both sides of the joint, and an effective thermal conductivity of the joint based on the length of the overlap and the temperature difference between the two ends of the overlap. This method would be somewhat impractical when a large number of joints is involved, since this would mean that many models would need to be constructed and tested unless all of the joints were standardized.

In the theoretical study of Veilleux and Mark,[125] the physical contact between the metal sheets was assumed to occur only under the head of the bolts fastening the sheets together. The good agreement between theory and experiment confirmed this assumption.

Bradley et al.[126] used a stress-freezing technique to determined the pressure distribution over the interface of a bolted joint. It was found that the interface pressure distribution depended upon the radius of the bolt, the bolt-head dimension, and the plate thickness.

The finite element analysis of Gould and Mikic[127,128] also considered bolted joints of smooth surfaces. The area of contact was measured by both optical and autoradiograph methods. There was good agreement between theory and experiment. The results indicated, in conformity with those of Bradley et al.,[126] that the interface pressure reduced from a maximum value at the bolt axis to zero at a distance of about 2 bolt diameters from the axis.

Roca and Mikic[129] also took surface roughness into consideration in their analytical study of thermal conductance of bolted joints. One significant conclusion of this work was that, for a given pair of plates and loading conditions, the radius of contact increased with the surface roughness. This means that the macroscopic constriction decreases as the surface roughness increases, while the opposite is true of the microscopic constriction.

A general expression capable of handling nonuniform pressure distributions for the thermal resistance in vacuum was derived by Yip.[130] His calculations indicated that nonuniform stress distributions did not appreciably affect the microcontact resistance. It should be noted, however, that the extent of the contact zone and, therefore, the macroscopic resistance, will still depend upon the stress distribution.

The conductance of two aluminum plates bolted together was investigated by Oehler et al.[131] The conductance values in air were found to be about twice the values obtained in vacuum, but the joints loaded with grease in a vacuum were only about 10% more conducting than the dry joints in a vacuum. No information was given about the surface texture of the plates. It was also found that the contact conductances based on steady-state tests were about 50% higher than those based on transient tests. Since it was stated that transient measurements were subject to greater degrees of error, the suitability of the transient technique becomes questionable.

Cylindrical Joints

When the heat flow is radial across a joint formed by two concentric cylinders, the contact pressure is not explicitly known but depends on the

1) initial interference or clearance between the cylinders,

2) differential expansion of the cylinders due to the temperature gradient caused by the heat flow,

3) thermal and mechanical properties of the cylinder materials, and

4) differential expansion due to the temperature drop ΔT at the interface.

Therefore, for a given pair of cylinders, the contact pressure depends upon the heat flux. It is also to be noted that ΔT is itself, by definition, dependent upon the contact conductance and, therefore, the contact pressure. In other words, the contact pressure and the temperature drop are interdependent.

In the work prior to the period under review, the resistance of cylindrical joints was usually estimated indirectly. In such a procedure, the overall resistance to heat flow from the fluid heating the inner of the two concentric cylinders to the coolant surrounding the outer cylinder is measured. The individual component resistances, except the contact resistance, are then either measured or estimated separately and subtracted from the overall resistance to obtain the contact resistance. One serious drawback of such a method is that large errors are likely to occur when the contact resistance is relatively small and is determined as the difference between two comparatively large resistances.

In the direct method, the temperatures are measured at various radial locations in the cylinders, and the temperature distributions are then extrapolated to obtain the temperature drop at the interface directly. Thus, this method is similar to the usual method for flat surfaces, except that the heat flux, rather than the implicit contact pressure, would be the independent variable.

Williams and Madhusudana[132] described a simple theoretical analysis of heat flow across cylindrical joints of similar materials in a vacuum. The theory showed that the contact pressure and, therefore, the solid spot conductance increased directly with heat flux. For stainless-steel specimens with initial clearance, the experimental results obtained by the direct method confirmed the theoretical findings. The theory also showed that, for specimens with initial interference fit, the contact pressures are so high that the contact resistance becomes insignificant. This was verified by the experimental observation that no measurable interface temperature drop existed for stainless-steel specimens with an initial interference fit. However, their experimental results for specimens with initial zero clearance showed no definite trends and were therefore inconclusive.

Direct measurements of resistance in a compound cylinder have also been reported by Hsu and Tam.[133] In this case, the cylinder was of aluminum alloy on which a stainless-steel tube was shrunk. The heat flow was radially outward, and, since aluminum has a higher coefficient of thermal expansion, it is to be expected that the resistance would reduce with heat flux.[134] This fact was confirmed by experiments conducted in air.

More recently, Madhusudana[135] extended the theory presented in Ref. 132 to include dissimilar materials, also taking into account the more refined general contact heat-transfer theories that had become available since the first theory was published. The following additional conclusions were drawn.

1) For a given heat flux, the material combination in which the inner cylinder has the higher α/E ratio would yield higher values of the contact conductance if the heat flow is radially outward; the opposite would be true for inward flow.

2) For cylindrical joints, the contact pressure increases with the surface roughness. Therefore, the contact conductance would be expected to increase with the surface roughness. However, since the constriction resistance also increases with roughness, the relation between conductance and roughness in the case of cylindrical contacts is more complex than for flat contacts.

Nuclear Reactor Fuel Elements

A considerable amount of analytical and experimental work was carried out in the 1950's and 1960's on the conductance and strength of nuclear elements.

Based on the Mikic model,[51] Jacobs and Todreas[136] proposed a correlation for the solid spot conductance in reactor fuel elements. This correlation was tested against the data of Dean,[137] Ross and Stoute,[138] and Rapier et al.[139] Dean's tests were actually conducted in an argon atmosphere, and Jacobs and Todreas deduced the solid spot conductance values assuming that the fluid conductance contribution was 10% of the total. Since the information regarding $|\tan\theta|$ was not available in most of the tests, the data for one run of each surface was first normalized before a comparison was made between the proposed correlation and the experimental results. Thus the agreement between the correlation and the data was forced to a certain extent.

A model (GEGAP-III) for the calculation of pellet-cladding conductance in boiling water reactor fuel rods was presented in Ref. 140. Separate expressions were given for the solid spot, gas, and radiant heat-transfer coefficients. Comparison with experimental values showed that this model slightly underestimated the conductances.

A review of methods applicable to the calculation of gap conductance in zircaloy-clad uranium dioxide fuel rods was reported by Lanning and Hann.[141] They recommended the use of the Jacobs-Todreas model (reduced by a factor of 4) for the prediction of solid spot conductance until more data became available. Their expression for the gas conductance made allowance for the reduction of gap width with the contact pressure. The work of Lanning and Hann was extended by Beyer et al.,[142] whose correlation for the solid spot conductance also took into account the waviness of the surfaces, but not the profile slope.

As mentioned previously, Garnier and Begej[81] measured the gap conductance between uranium dioxide and zircaloy-4 surfaces in nominal contact. The experiments with helium, argon, and a 50:50 mixture of helium and argon indicated a continual increase of gas conductance with temperature. This is in contrast to the trend predicted by, for example, GAPCON-Thermal-2.[142]

Experimental results for the conductance of zircaloy-2/uranium dioxide interfaces have also been reported by Cross and Fletcher[143] and Madhusudana.[144] Tests were conducted in a vacuum, as well as in atmospheres of argon and helium. The improvement in conductance due to the presence of helium ranged from about 800 to 60% as the contact pressure increased from 0.89 to 20.13 MPa. Over the same range, the improvement due to the presence of argon ranged from about 400 to 10%.

A correlation for the solid spot thermal conductance of zircaloy-2/uranium dioxide interfaces has been proposed by Madhusudana and Fletcher.[145] This correlation considers all available data on direct measurements for this joint combination and thus includes data in Refs. 136, 137, 143, 145, and 146. This correlation takes into account the variation in the mean junction temperature obtained in the tests by different investigators, but does not include the effect of slope since, as pointed out earlier in this section, this information is not reported in most of the literature reviewed. The following correlation fitted 78 data points with remarkably small scatter:

$$h\sigma/k = 12.29\times10^{-3}\,(P/H)^{0.66} \tag{28}$$

It was suggested that further work on this type of contacts should include: 1) experimental investigation of the effect of varying the mean junction temperature; 2) quantitative evaluation of surface parameters, other than roughness, on the solid spot conductance; and 3) direct measurement (in a vacuum) of the solid spot conductance over the pressure range $0.001 < P/H < 0.005$.

Recommendations for Future Work

The preceding review of the research on contact heat transfer over the past decade identifies the following as some areas where need exists for further research.

1) Resistance of noncircular constrictions located at the ends of semi-infinite cylinders or prisms.

2) Conductance of rough wavy surfaces and comparison of the performance of these surfaces with that of rough flat surfaces.

3) Accommodation coefficient for practical gas/solid interfaces.

4) Determination of a reliable effective gap width for the calculation of conduction through the interstitial gas.

5) A theory for the explanation of the rectification effect observed in similar materials in contact.

6) Effect of mean-junction temperature on the conductance of nuclear fuel elements. (Experimental data over a significant range of contact pressures are also lacking for nuclear fuel elements.)

7) Resistance of a circular annulus and the pressure distribution in a bolt joint necessary to determine the conductance of such joints.

8) Direct experimental measurement of the thermal conductance of cylindrical joints and the extension of the present theory for such joints to include the effect of the interstitial medium on the heat transfer.

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