A NEW GASEOUS GAP CONDUCTANCE RELATIONSHIP

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A new relationship for predicting the gaseous gap conductance between the fuel and clad of a nuclear fuel rod is derived. This relationship is derived from purely analytical considerations and represents a departure from approaches taken in the past. A comparison between the predictions from this new relationship and experimental measurements is presented and the agreement is very good. Predictions can be generated relatively quickly with this relationship making it attractive for fuel pin analysis codes.

INTRODUCTION

The thin gap between the fuel and clad in a nuclear fuel rod constitutes a substantial thermal resistance to the flow of heat from the rod. This has prompted the nuclear industry to devote a considerable amount of attention to methods for predicting the heat transfer across this gap.

Heat is transferred across the fuel-clad gap by gaseous conduction and thermal radiation. When the fuel and clad are in contact, another heat transfer mode also contributes to the total heat conductance. This mode is known as contact conductance, and recently methods have become available for accurately predicting this contribution.[1,2] Under accident conditions, thermal radiation may comprise a significant portion of the total heat transfer. Under normal operating conditions, however, thermal radiation is a small portion of the total heat transfer, and gaseous conduction is generally the primary mode of heat transfer across the gap. Unfortunately, difficulties have been encountered in accurately predicting gaseous conduction.

Gaseous conduction is typically predicted by applying a form of the temperature jump heat conduction equation. Knudsen number effects are generally ignored, and this form is used from the continuum to the free molecule regime. The temperature jump lengths used in these equations are evaluated with relations based on kinetic theory. Although this practice has become widely accepted, difficulties have been experienced in properly accounting for gas mixture and roughness effects. Several different forms of equations have been proposed[3] for dealing with gas mixture effects, but it is not clear which form is preferable. Roughness effects have been taken into account by applying an empirical correction factor to the fuel-clad separation distance term in the heat conduction equation. However, this practice has been responsible for inaccurate gap conductance predictions.[4]

THEORETICAL CONSIDERATIONS

When the characteristic length of a gaseous heat conduction geometry becomes small, Fourier's law cannot be used directly for predicting heat transfer because of noncontinuum effects. The length at which noncontinuum effects become important can be estimated with the Knudsen number (the ratio of the mean-free-path and the characteristic length). Once the Knudsen number exceeds 0.01, errors can result from ignoring noncontinuum effects.

Noncontinuum effects have been taken into account by employing a jump in temperature at the bounding surfaces. Temperature jump is incorporated into the heat conduction equation by adding temperature jump lengths to the gap length. The resulting gap conductance equation is written as (see Nomenclature on p. 73)

$$h = \frac{k}{\delta + (g_1 + g_2)} \quad . \tag{1}$$

Temperature jump lengths have generally been estimated with relationships derived from kinetic theory. These relations all have a similar form for pure gases. The theory from Knudsen[5] can be used to derive the following expression for the temperature jump lengths:

$$(g_1 + g_2) = \frac{k}{P}\left(\frac{a_1 + a_2 - a_1 a_2}{a_1 a_2}\right)\left(\frac{\gamma - 1}{\gamma + 1}\right) \times \left(\frac{8\pi MT}{\mathcal{R}}\right)^{1/2} . \quad (2)$$

If the accommodation coefficient portion of this expression is altered, other proposed forms of temperature jump length relationships can be obtained. For example, if the accommodation coefficients of both surfaces are equal ($a_1 = a_2 = a$), then the relation proposed by Kennard[6] is obtained. Although equations of this form have become widely accepted for predicting temperature jump lengths with pure gases, the extension of this theory to gas mixtures is not trivial.

The approach selected here for dealing with gas mixtures is based on techniques that have been developed to estimate the thermal conductivity of gas mixtures. Mixture conductivities can be evaluated with an equation of the following form[7]:

$$k_{mix} = \sum_{i=1}^{n} \frac{x_i k_i}{\Gamma_i} , \quad (3a)$$

where

$$\Gamma_i = \sum_{j=1}^{n} x_j \Phi_{ij} \quad (3b)$$

and Φ_{ij} is a function of either the component thermal conductivities and molecular weights or viscosities and molecular weights. Texts in elementary kinetic theory derive expressions for the thermal conductivity of a pure gas by summing the energies of the molecules that cross a fictitious plane situated in the gas. If this viewpoint is extended to gas mixtures, Eq. (3a) effectively partitions the energy crossing the plane into components of $x_i k_i/\Gamma_i$. These components have been applied directly to pure gas temperature jump equations to obtain components of heat conductance. The sum of these parallel conductances represents the total conductance of the gas mixture. This approach was used by Hagrman[8] in obtaining the following equation for the heat transfer coefficient of a gas mixture:

$$h = \sum_{i=1}^{n} \left\{ \frac{x_i k_i}{\Gamma_i} \Big/ \left[\delta + \frac{x_i k_i}{P_i \Gamma_i} \left(\frac{a_1 + a_2 - a_1 a_2}{a_1 a_2} \right)_i \times \left(\frac{\gamma - 1}{\gamma + 1} \right)_i \left(\frac{8\pi M_i T}{\mathcal{R}} \right)^{1/2} \right] \right\} . \quad (4)$$

This expression can be simplified somewhat by replacing P_i with Px_i.

Equation (4) was derived for smooth flat surfaces. All surfaces, however, are microscopically rough to some extent. A method for including the effects of roughness has been presented by Yovanovich et al.[9] This method modeled two rough surfaces with Gaussian height distributions by considering a rougher combined surface and a smooth flat plate. This configuration is illustrated in Fig. 1. The standard deviation of the new combined surface is

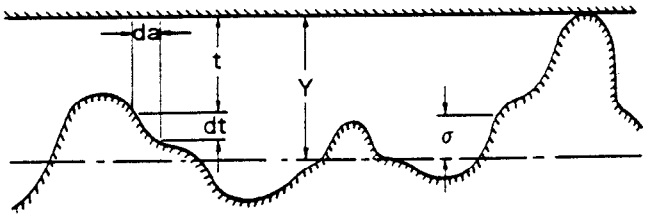

Fig. 1. An illustration of the rougher combined surface and the smooth flat plate.

$$\sigma = (\sigma_1^2 + \sigma_2^2)^{1/2} . \quad (5)$$

The heat flow between the surfaces was assumed to be confined within parallel flux tubes that spanned the surfaces. This one-dimensional simplification is justified because rough surface asperities typically have included angles that range from 160 to 170 deg. Therefore, rough surfaces can be characterized as gentle rolling hills as opposed to rugged steep mountains. It was shown that the cross-sectional area of flux tubes with lengths between t and $t + dt$ is

$$da = \frac{A}{\sqrt{2\pi}} \exp\left[-\left(\frac{Y}{\sigma} - \frac{t}{\sigma} \right)^2 \Big/ 2 \right] d\left(\frac{t}{\sigma} \right) . \quad (6)$$

This expression is valid for surfaces in contact as well as those not in contact. The total heat exchange between the surfaces is found by summing the contributions from all flux tubes. The summation process can be replaced by a continuous integral giving

$$h = \frac{1}{A} \int_0^{A_g} \frac{k\,da}{t + (g_1 + g_2)} . \quad (7)$$

The projected gap area A_g is equal to the apparent area A when the surfaces are not in contact. When the surfaces are in contact, A_g is somewhat less than A. Note that the surfaces have been assumed to be isothermal. This assumption is common in contact conductance studies. The new gap conductance correlation is obtained by incorporating Eqs. (4) and (6) into Eq. (7), nondimensionalizing, and applying the proper limits:

$$h = \frac{1}{\sigma\sqrt{2\pi}} \sum_{i=1}^{n} \frac{k_i x_i}{\Gamma_i} \int_0^{\infty} \frac{\exp\left[-\left(\frac{Y}{\sigma} - \frac{t}{\sigma} \right)^2 \Big/ 2 \right] d\left(\frac{t}{\sigma} \right)}{\frac{t}{\sigma} + \Omega_i} , \quad (8a)$$

where

$$\Omega_i = \frac{k_i}{\sigma P \Gamma_i}\left(\frac{a_1 + a_2 - a_1 a_2}{a_1 a_2}\right)_i \left(\frac{\gamma - 1}{\gamma + 1}\right)_i \left(\frac{8\pi M_i T}{\mathcal{R}}\right)^{1/2} . \quad (8b)$$

Obtaining a closed form solution of the integral in Eq. (8a) is not trivial, and numerically integrating this equation in a fuel pin analysis code would require too much time. The calculational process can be accelerated, however, by isolating the roughness effects. Equation (8a) can be rewritten as

$$h = \sum_{i=1}^{n} \frac{k_i x_i}{\sigma \Gamma_i}\left(\frac{R_i}{\frac{Y}{\sigma} + \Omega_i}\right) , \quad (9a)$$

where

$$R_i = \frac{\left(\frac{Y}{\sigma} + \Omega_i\right)}{\sqrt{2\pi}} \int_0^\infty \frac{\exp\left[-\left(\frac{Y}{\sigma} - \frac{t}{\sigma}\right)^2 \Big/ 2\right] d\left(\frac{t}{\sigma}\right)}{\frac{t}{\sigma} + \Omega_i} ; \quad (9b)$$

R_i is the roughness factor and is a function only of the Y/σ and Ω_i dimensionless variables. Since R_i is a function of dimensionless variables, the R_i values can be calculated in advance and stored in the code. They would then be retrieved for use in Eq. (9a) during the execution of the program.

The roughness factor is shown plotted in Fig. 2 versus the dimensionless gap. The curves correspond with different dimensionless temperature jump lengths. The figure shows that roughness effects die out rapidly when gap spacing is increased and can be ignored when $Y/\sigma > 10$. Also, R_i is less than unity when Ω_i is large. Ignoring roughness effects in this case would result in a nonconservative gap conductance estimate. However, when Ω_i is small, the roughness factor may significantly exceed unity, and roughness effects would augment the gap conductance. Note that Ω_i can be decreased by either decreasing the gas temperature or by increasing the gas pressure or surface roughness. This may partially explain why an increase in gap conductance was measured when the gas pressure was increased.[10]

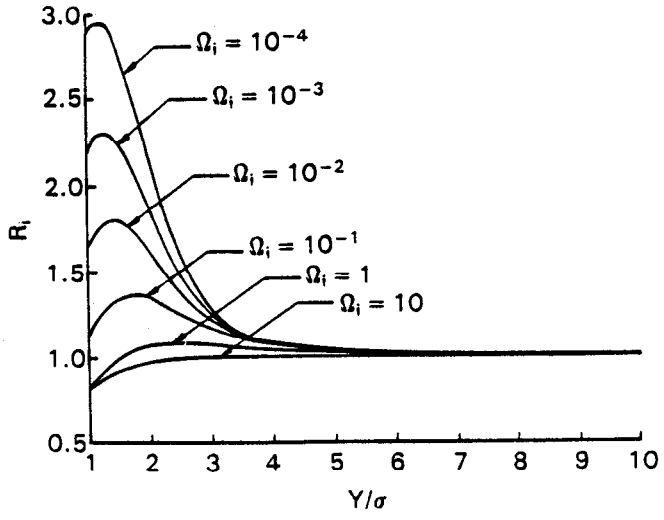

Fig. 2. Roughness factor versus dimensionless gap for different dimensionless temperature jump lengths.

COMPARISON WITH MEASUREMENTS

The experimental data of Garnier and Begej[11] were chosen for the comparison with the predictions from the new gap conductance relationship. All of the noncontact data obtained with the modified pulse design technique were used. This included 99 gap conductances measured under a variety of gas temperature, gas mixture, surface roughness, and gap conditions. The gas temperature ranged from 293 to 873 K; pure helium, pure argon, one helium/argon mixture, and three different helium/xenon mixtures were used. The UO_2 and Zircaloy test sample pairs were prepared with three different surface morphologies, and the gaps ranged from 8.6 to 33.0 μm. The report for these data contained all of the information necessary to test the new gap conductance relationship with the exception of the accommodation coefficients. The accommodation coefficients initially selected for this comparison were taken from the work of Thomas and Loyalka.[12,13] The predictions with these accommodation coefficients agreed very well with measurements for moderately rough and very rough surfaces. Predictions for smooth ($\sigma = 0.37$-μm) surfaces, however, were slightly greater than measurements. This was likely due to the ability to control the cleanliness of the smooth surfaces better than the other surfaces. Ultraclean surfaces typically have accommodation coefficients that are less than comparable "engineering" surfaces. This effect was taken into account by selecting accommodation coefficients for the smooth surfaces that were midway between those reported by Thomas and Loyalka[12,13] and those reported by Hagrman.[8] Unfortunately, the temperature dependence of the accommodation coefficients used in this comparison was not known.

The comparison of the gap conductance predictions and measurements is shown in Fig. 3. The dashed lines in the figure represent the reported $\pm 12\frac{1}{2}\%$ uncertainty in the experimental data. The majority of the predictions fall within these uncertainty limits. Recall that the new gap conductance relationship requires the dimensionless gap. The modified pulse design experimental technique, however, does not require gap measurements to evaluate gap conductance. Therefore, the

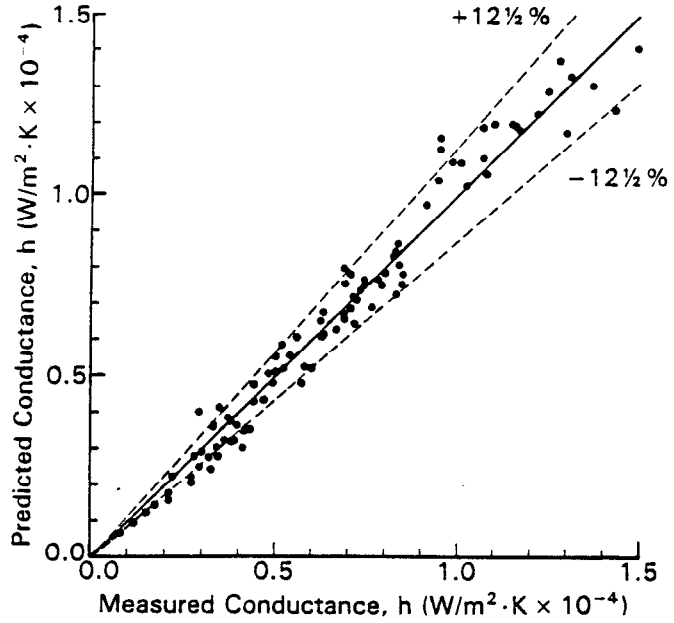

Fig. 3. Comparison of predicted and measured gaseous gap conductance.

$\pm 12\frac{1}{2}\%$ uncertainty does not include the uncertainty in gap measurements, which ranged from 7.3 to 61.9%. If the uncertainty in the gap measurements is included, all of the predictions fall within the experimental uncertainty limits. The agreement between the predictions and measurements is very good indeed; however, agreement would probably be improved further by including the temperature dependence of the accommodation coefficients.

The agreement between the measurements and predictions deteriorates if the roughness factor is eliminated from the calculations. This becomes particularly apparent with small dimensionless gaps. An example of this effect is shown in Fig. 4 where the percent difference between the measured and predicted gap conductance versus the gas temperature is presented. A single set of experimental data were used for this comparison. The data were obtained with pure helium, fully rough surfaces ($\sigma = 18.9\ \mu m$), and a small dimensionless gap ($Y/\sigma = 1.75$). Two lines in the figure represent predictions that included and neglected roughness effects ($R_i = 1$), respectively. When roughness effects are ignored, the percent difference between measurements and predictions is a function of the gas temperature. When the roughness factor is included in the calculations, however, the gas temperature dependence is eliminated. The total experimental uncertainty in this data set is ~20%. Although including the roughness factor did not reduce the percent difference to zero for this particular data set, the predictions are well within the total uncertainty. When roughness effects are ignored, however, the predictions for the low gas temperature data were well outside the uncertainty limits.

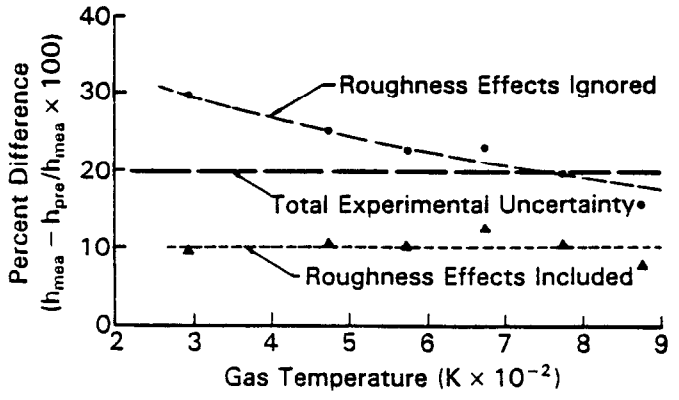

Fig. 4. Comparison between including and neglecting roughness effects in the gap conductance predictions.

CONCLUDING REMARKS

The purely analytical approach taken in deriving the new gaseous gap conductance relationship represents a departure from past approaches. The new relationship addresses previously unexplained effects that have been observed in experimental programs. The very good agreement between measurements and predictions certainly supports and strengthens the new analytical approach. Gaseous gap conductance can be calculated relatively quickly with the new relationship making it attractive for fuel rod analysis codes.

NOMENCLATURE

a = cross-sectional area defined in Eq. (6)

a_1, a_2 = accommodation coefficients of the clad and fuel, respectively

A = apparent fuel (or clad) surface area

A_g = projected gap area, $A_g = A -$ (real contact area)

g_1, g_2 = temperature jump length for the clad and fuel, respectively

h = gaseous gap conductance

k = gas thermal conductivity

k_i = thermal conductivity of the i'th gas species

k_{mix} = thermal conductivity of the gas mixture

M = gas molecular weight

M_i = molecular weight of the i'th gas species

P = total gas pressure

P_i = partial pressure of the i'th gas species

χ_i = roughness factor defined in Eq. (9b)

$\mathcal{R}$ = universal gas constant

t = roughness height coordinate

T = gas temperature

x_i = mole fraction of the i'th gas species

Y = gap between the surface mean planes

γ = ratio of specific heats

Γ_i = thermal conductivity factor for the i'th gas species defined in Eq. (3b)

δ = gap between two flat surfaces

σ = effective surface roughness defined in Eq. (5)

σ_1, σ_2 = standard deviation of the surface heights of the clad and fuel, respectively

Φ_{ij} = gas mixture coefficient

Ω_i = sum of the clad and fuel dimensionless temperature jump lengths for the i'th gas species defined in Eq. (8b)

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