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A STATISTICAL MODEL TO PREDICT THERMAL GAP CONDUCTANCE BETWEEN CONFORMING ROUGH SURFACES

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Abstract

New gap conductance models are developed to account for gas properties and pressure, and surface roughness and its deformation under load. Both slip and rarefied gas conditions are incorporated in the thermal model. Dimensionless gap conductance correlations are presented in integral and graphical form. The conductance is dependent upon a modified Knudsen number, relative gap separation and a conductivity ratio. The proposed correlations are in good agreement with limited experimental data.

Nomenclature

A_a	= apparent or nominal contact area
A_g	= projected gap area, $A_g = A_a - A_r$
a_g	= gap area variable
A_r	= real contact area
B	= gas parameter, $B = (2\gamma/\gamma + 1)/Pr$
C_g	= dimensionless gap conductance, $C_g = \sigma h_g/k_s$
g_1, g_2	= temperature jump distance for surface 1 and surface 2 respectively
H	= hardness of the softer contacting solid
h_g	= gap conductance, $h_g = 1/(R_g A_a)$
K	= gas-solid conductivity ratio, $K = k_g/k_s$
k_1, k_2	= conductivities of the contacting solids
k_g	= gas conductivity
k_s	= harmonic mean conductivity, $k_s = 2k_1k_2/(k_1 + k_2)$
M	= gas parameter, $M = \alpha\beta\Lambda/\sigma$
$\mathcal{M}$	= molecular weight of the gas
p	= apparent contact pressure
P_g, P_{go}	= gas pressure and gas pressure at reference conditions
Pr	= Prandtl number, $Pr = \mu c_p/k_g$
Q	= heat flow rate
q	= heat flux
R_g	= gap resistance
R_{gi}	= gap resistance of an individual flux tube
$\mathcal{R}_o$	= universal gas constant
T_1, T_2	= surface temperatures of the contacting solids
T_o	= reference gas temperature
T	= mean gas temperature, $T = (T_1 + T_2)/2$
t	= local gap thickness
Y	= separation between the surfaces

Greek Symbols

α	= accommodation parameter
α_1, α_2	= accommodation coefficients for solid 1 and solid 2 respectively
γ	= ratio of specific heats, $\gamma = c_p/c_v$
Λ, Λ_o	= molecular mean free path
σ	= effective surface roughness, $= \sqrt{\sigma_1^2 + \sigma_2^2}$
σ_1, σ_2	= standard deviation of surface heights of surface 1 and 2 respectively

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Introduction

The purpose of this paper is to present a comprehensive method for calculating the heat transfer which occurs across the gap between conforming rough surfaces under the presence of an interstitial gas. The model requires that the surfaces have Gaussian surface height distributions, having no preferred lay direction, and that the deformation of the contacting asperities will be plastic in nature. Although these restrictions apply to this particular solution, there is no reason why the basic approach suggested here cannot be used in more general surface contact situations.

Decreases in gas pressure which, according to the kinetic theory of gases, lead to a reduction in the gas conductivity can successfully be modelled by the methods presented here.

Thermal Gap Conductance: Geometric Physical and Thermal Assumptions

The gap conductance model developed here is based on the following assumptions:

(1) The surfaces are microscopically rough but macroscopically conforming.
(2) As mentioned in the introduction, the contacting surfaces have isotropic Gaussian surface height distributions and contacting asperities of the softer solid deform plastically.
(3) The contact spots, and adjacent surfaces not in contact, are isothermal, each having the temperature extrapolated from the body of the solids.
(4) The total heat flow rate can be separated into independent heat flow rates: contact and gap flow rates.
(5) Noncontinuum gas effects must be taken into account.
(6) The variable gap thickness will influence the gap conductance and must thus be taken into account.
(7) The surfaces are clean, free of oxides, films, etc.
(8) Radiative heat transfer is negligible.

Slip Flow Development

Consider heat transfer by conduction through a gas layer between two parallel isothermal surfaces. At atmospheric pressure, and with a fairly large distance between the surfaces, the temperature distribution across the gap will be seen to be linear if the temperature difference across the surfaces is not large. The resistance to heat transfer across such a gap, under these continuum conditions, can be written as

$$R_{g,\infty} = t/(k_g A_g) \tag{1}$$

If, however, the gas pressure is reduced, a nonlinear temperature profile in the gap is observed, with distinct discontinuities occurring between the wall temperature and the gas temperature at the wall (see Fig. 1).

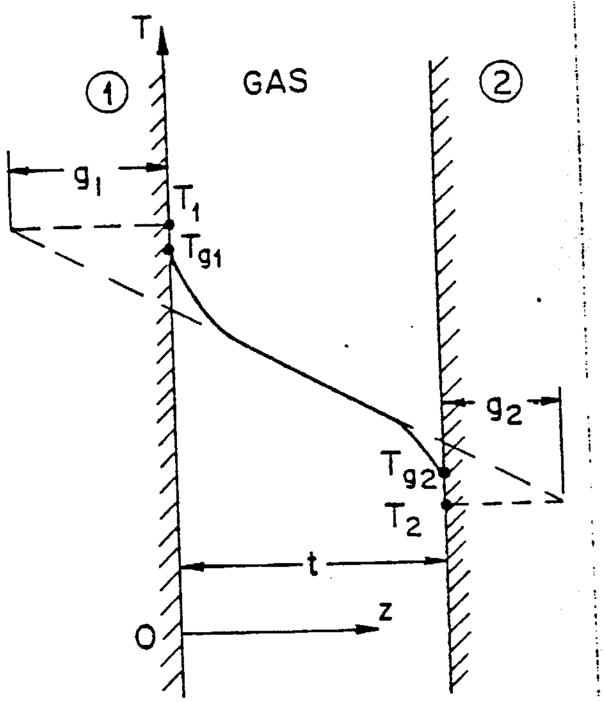

Fig. 1 Parallel Isothermal Plates Showing Temperature Jump Phenomena

This discontinuity, or temperature jump, results from an incomplete energy transfer between gas molecules and the molecules of the wall material.

The magnitude of the temperature jump depends on many factors, some of which are

(1) The ratio of molecular weights of gas and wall material.
(2) Surface condition and oxide layers on the surface.
(3) The gas molecular mean free path.

Traditionally, the temperature jump has been modelled by considering the extra distances, g_1 and g_2, which must be added to the gap thickness to maintain the temperature gradient as linear between the wall temperatures. [1]

An expression relating the temperature jump, through the temperature jump distance, g, to the accommodation coefficient can be obtained from the kinetic theory of gases and is presented directly here as

$$g_1 = \frac{(2 - \alpha_1)}{\alpha_1} \frac{2\gamma}{(\gamma + 1)} \frac{1}{Pr} \Lambda \tag{2}$$

If we define the accommodation parameter, α, as

$$\alpha = \frac{(2 - \alpha_1)}{\alpha_1} + \frac{(2 - \alpha_2)}{\alpha_2} \tag{3}$$

the temperature jump distances will be given by

$$g_1 + g_2 = \alpha \frac{2\gamma}{(\gamma + 1)} \frac{1}{Pr} \Lambda \tag{4}$$

Collecting together the variables related to the gas behaviour the parameter B is defined

$$B = \frac{2\gamma}{(\gamma + 1)} \frac{1}{Pr} \tag{5}$$

Recognizing that the mean free path, Λ, is proportional to temperature and inversely proportional to pressure we can say

$$g_1 + g_2 = \alpha B \Lambda_o \left(\frac{T}{T_o}\right)\left(\frac{P_{go}}{P_g}\right) \tag{6}$$

where the subscripted values represent some reference condition.

Adding the temperature jump distances to the gap thickness yields the following expression for the resistance to heat transfer across the gap for parallel surfaces in the slip flow regime.*

$$R_{g,sl} = \left[t + \alpha B \Lambda_o \left(\frac{T}{T_o}\right)\left(\frac{P_{go}}{P_g}\right)\right] / (k_g A_a) \tag{7}$$

Transition Flow Development

As the gas pressure in the gap is reduced further such that the ratio of the molecular mean free path divided by the gap thickness (defined as the Knudsen number) becomes very large a condition known as free molecular flow results. In this condition each gas molecule travels directly from one surface to the other without experiencing any other collisions, and, as a result of this, the gap thickness between the surfaces has no physical significance.

An expression for the heat transfer between two surfaces in the free molecular regime (Kn >> 1) is given by Kaganer [2] as

$$Q_{fm} = \bar{\alpha} \frac{(\gamma + 1)}{(\gamma - 1)} \sqrt{\frac{R_o}{8\pi}} \frac{P_g}{\sqrt{MT}} A_{g1}(T_2 - T_1) \tag{8}$$

where

$$\bar{\alpha} = 1/\left[\frac{1}{\alpha_1} + \frac{A_{g1}}{A_{g2}} \left(\frac{1}{\alpha_2} - 1\right)\right] \tag{9}$$

* Note: The authors originally thought that the above expression could only be used in the slip flow regime but later found that this expression is valid over the entire free molecule to continuum range.

If the assumption is made that $A_{g1} = A_{g2}$ for two rough surfaces in contact we can say

$$\frac{1}{\bar{\alpha}} = (\frac{1}{\alpha_1} + \frac{1}{\alpha_2} - 1) = \frac{\alpha}{2} \quad (10)$$

using our previous definition of the accommodation parameter.

Rewriting the expression in terms of the resistance gives

$$R_{g,fm} = \alpha \frac{(\gamma - 1)}{(\gamma + 1)} \sqrt{\frac{2\pi}{R_o}} \frac{\sqrt{MT}}{P_g} / A_g \quad (11)$$

The constant $\sqrt{R_o/2\pi}$ is equal to 36.38 if $q = Q/A_g$ is expressed in W/m^2, P_g in N/m^2, and T in °K.

The above expression for resistance is only valid for very large values of the Knudsen number. As the gas pressure is increased the probability of a gas molecule travelling unimpeded between the surfaces rapidly becomes small. Collisions between gas molecules, typical of heat conduction in the continuum regime, begin to predominate as the pressure approaches atmospheric from vacuum conditions.

It has been demonstrated experimentally that heat conduction in the transition regime between the free molecular flow regime and the continuum regime can be predicted sufficiently accurately by summing the heat fluxes in parallel, yielding the following relation

$$q_{tr} = q_\infty/[1 + q_\infty/q_{fm}] \quad (12)$$

For a fixed system the heat flux can be expressed as $q = (T_2 - T_1)/A_g R_g$, allowing equation (12) to be rewritten as

$$R_{g,tr} = R_{g,\infty} + R_{g,fm} \quad (13)$$

The resistance to heat conduction across the gap for parallel isothermal surfaces in the transition regime is thus

$$R_{g,tr} = [t + \alpha\frac{(\gamma - 1)}{(\gamma + 1)} \sqrt{\frac{2\pi}{R_o}} \frac{\sqrt{MT}}{P_g} k_g]/(k_g A_g) \quad (14)$$

The above expression bears a striking resemblance to equation (7) developed earlier for conduction in the slip regime. Indeed, the term:

$$\alpha \frac{(\gamma - 1)}{(\gamma + 1)} \sqrt{\frac{2\pi}{R_o}} \frac{\sqrt{MT}}{P_g} k_g \quad (15)$$

is identical to the term:

$$\alpha B \Lambda_o (\frac{T}{T_o})(\frac{P_{go}}{P_g}) \quad (16)$$

The equivalency of these two terms is best illustrated by Dushman [3], pg 56 , during his development of another similar expression for heat loss from parallel plates at low gas pressures.

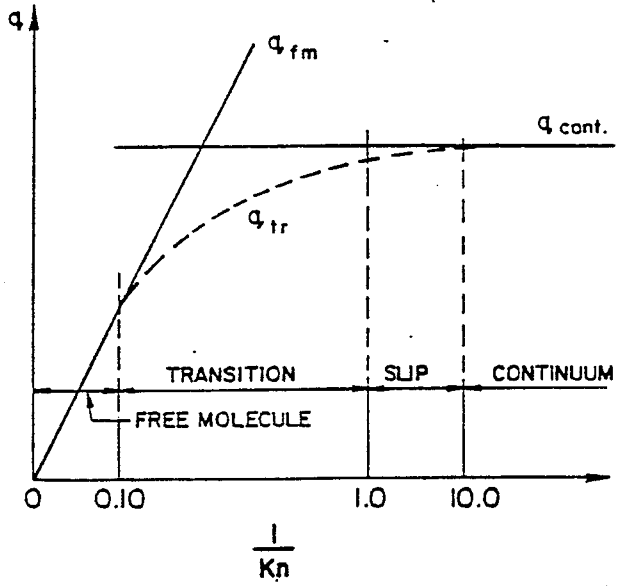

Fig. 2 Heat Flux Relations as a Function of Inverse Knudsen Number

The two expressions for gap resistance between parallel plates developed thus far will both model the heat transfer between parallel isothermal surfaces over the full range of Knudsen number. Figure 2 illustrates the parallel addition of heat fluxes used in developing the second model. The various heat transfer regimes are noted on the graph but should not be thought of as indicating a specific mode of conduction in a given Knudsen range but should be considered as a guide to the mix between free molecular flow and continuum conditions in that range.

Application of the Model to Rough Surfaces

In considering heat transfer across the gap between contacting rough surfaces, the variable gap thickness presents a formidable obstacle to determining the gap resistance. In areas where the gap thickness is thin, the resistance to heat transfer will be very different from areas which have a large gap thickness; the ratio of free molecular flow to continuum flux will also differ with the local gap thickness (see Fig. 3). This large difference in resistance between thin and thick gap areas would in reality cause a variation in the surface temperatures but if the surfaces are considered to be isothermal the resistances of the various gap thicknesses can be added in parallel to find the total gap resistance. The effect of prescribing isothermal surfaces is to slightly overpredict the gap conductance or underpredict the gap resistance.

The assumption of isothermal surfaces is in keeping with the extremely useful concept of thermal contact resistance where the extrapolated interface temperature difference is used for all contacts regardless of their size and individual constriction parameters.

The parallel plate model is applied to the variable gap by determining the fraction of projected gap area having a given thickness, finding the resistance for this area, and then adding it

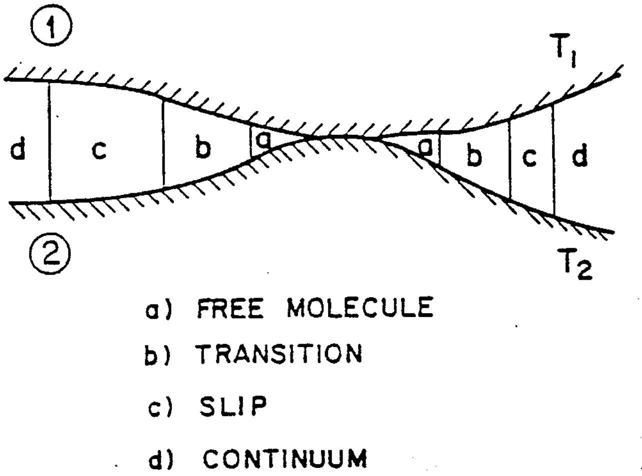

Fig. 3 Cross-Section Through Contacting Surfaces Illustrating the Range of Flux Conditions Occurring in the Gap

in parallel with the resistances of other gap areas, ranging over the full gap area and all possible thicknesses in the process.

In this integral method the slope of the surface is disregarded but, as the mean slope of most rough surfaces is usually under ten percent, the error introduced by this assumption can be considered small for most engineering purposes.

The parallel plate model is first applied to an elemental flux tube spanning the gap between the two isothermal surfaces as follows:

Heat Transfer Relations for an Elemental Flux Tube in the Gap

The resistance for an elemental flux tube spanning the gap between two surfaces can be given as follows:

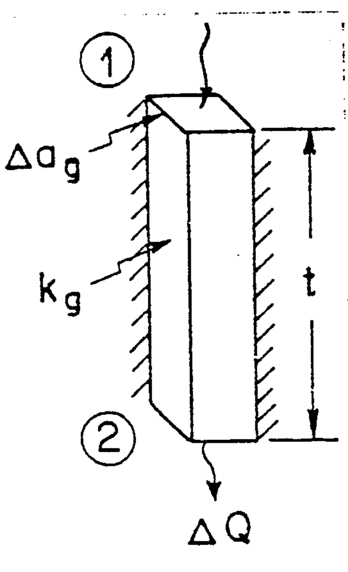

Fig. 4 Heat Transfer Relations for an Elemental Flux Tube in the Gap

For continuum conditions

$$\frac{\Delta Q}{\Delta a_g} = k_g(T_1 - T_2)/t \tag{17}$$

Let this be the ith flux tube

$$R_{gi} = \frac{\Delta T}{\Delta Q_i} \tag{18}$$

$$\therefore \quad R_{gi} = t_i/(\Delta a_g k_g) \tag{19}$$

For the slip flow model, $g_1 + g_2$ can be added to the gap thickness giving,

$$R_{gi} = \left[t_i + \alpha B \Lambda_o \left(\frac{T}{T_o}\right)\left(\frac{P_{go}}{P_g}\right)\right]/(\Delta a_g k_g) \tag{20}$$

Or, in the case of the alternative development,

$$R_{gi} = \left[t_i + \alpha\frac{(\gamma - 1)}{(\gamma + 1)}\sqrt{\frac{2\pi}{R_o}}\,\frac{\sqrt{MT}}{P_g}\,k_g\right]/(\Delta a_g k_g) \tag{21}$$

Combining Surfaces Having Gaussian Height Distributions

Contact between two rough surfaces having Gaussian height distributions can be modelled by considering a rougher combined surface, still Gaussian in distribution, in contact with a smooth flat plane. The standard deviation of this new combined surface is given by

$$\sigma = \sqrt{\sigma_1^2 + \sigma_2^2} \tag{22}$$

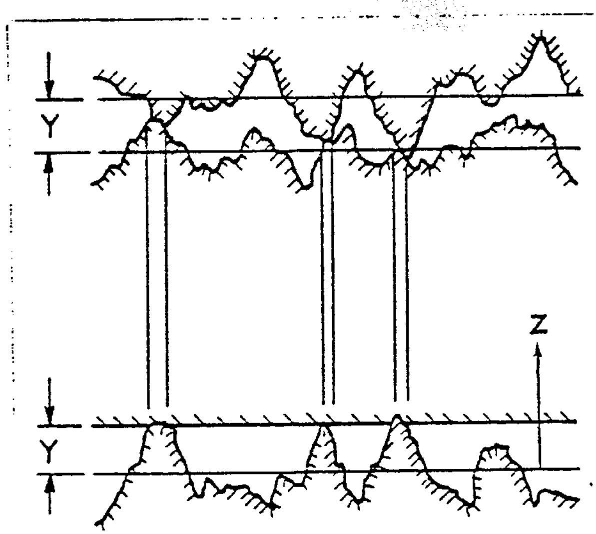

Fig. 5 Combining Two Rough Surfaces to Yield the Equivalent Rough Surface in Contact with a Smooth Plane

The area ratio in contact for first loading between the two rough surfaces is given by

$$\frac{P}{H} = \frac{A_r}{A_a} = \frac{1}{\sqrt{2\pi}}\int_{Y/\sigma}^{\infty} e^{-s^2/2}\,ds \; ; \; s = z/\sigma \tag{23}$$

which is usually written

$$\frac{P}{H} = \frac{A_r}{A_a} = \frac{1}{2}\,\mathrm{erfc}(\Upsilon/\sqrt{2}\sigma) \tag{24}$$

The area not in contact, or the gap area, is thus given by

$$A_g = \frac{A_a}{\sqrt{2\pi}}\int_{-\infty}^{\Upsilon/\sigma} e^{-s^2/2}\,ds \tag{25}$$

Introducing the variable t as the local gap thickness between the combined rough surface and the intersecting smooth plane allows us to describe the gap area below a given thickness as

$$A_g(t/\sigma) = \frac{A_a}{\sqrt{2\pi}}\int_{-\infty}^{(\Upsilon/\sigma\, -\, t/\sigma)} e^{-s^2/2}\,ds \tag{26}$$

At this point the variable $a_g = A_g(t/\sigma)$ can be introduced freeing A_g to mean the total gap area in any contact situation. The derivative of the above expression with respect to the gap thickness will relate how the gap area changes as a function of gap thickness.

$$\frac{da_g}{dt} = \frac{A_a}{\sigma\sqrt{2\pi}}\exp[-(\Upsilon/\sigma - t/\sigma)^2/2] \tag{27}$$

Gap Conductance Integrals

If the flux tubes spanning the gap are developed by considering all of the gap area da_g having a thickness between t and t + dt the follow situation results.

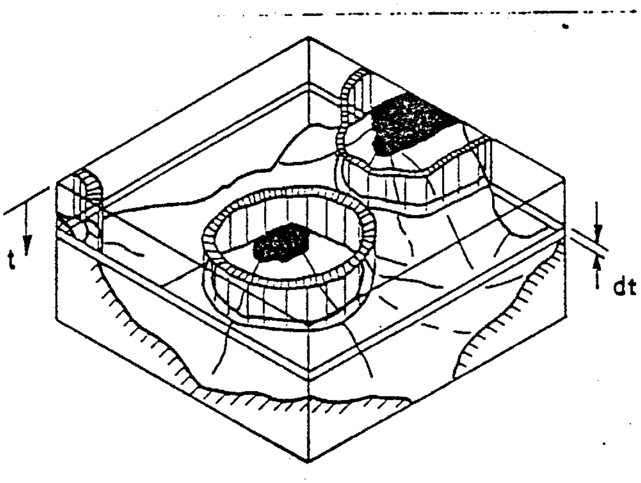

Fig. 6 Combined Rough Surface Illustrating a Single Flux Tube Spanning a Given Gap Thickness Between the Surfaces

Flux tubes, or sheets, are now seen to exist surrounding contact spots such that a given thickness has associated with it a flux tube of a certain area. As the flux tubes are considered to have adiabatic boundaries the fact that any given flux tube is discontinuous, as shown in the diagram, is irrelevant in calculating the gap conductance.

The total gap resistance can also be seen to be the sum of the individual flux tube resistances in parallel

$$\frac{1}{R_g} = \sum_i \frac{1}{R_{gi}} \tag{28}$$

The gap resistance for both developments respectively becomes

$$\frac{1}{R_g} = \sum_i (\Delta a_g k_g)/[t_i + \alpha B\Lambda_o(\frac{T}{T_o})(\frac{P_{go}}{P_g})] \tag{29}$$

and

$$\frac{1}{R_g} = \sum_i (\Delta a_g k_g)/[t_i + \alpha\,\frac{(\gamma - 1)}{(\gamma + 1)}\sqrt{\frac{2\pi}{R_o}}\,\frac{\sqrt{MT}}{P_g}\,k_g] \tag{30}$$

The summation process can be dropped in favour of integration giving

$$\frac{1}{R_g} = \int_0^{A_g} \frac{k_g}{[t + \alpha B\Lambda_o(\frac{T}{T_o})(\frac{P_{go}}{P_g})]}\,da_g \tag{31}$$

To solve the above integration the relationship between gap thickness and gap area, $[t = t(a_g)]$, is required. A more convenient integration results if, instead of integrating over the gap area, a change of variable is made and the integration occurs over the gap thickness. Using the differential relationship developed in the last section and non-dimensionalizing the integral gives

For the slip development

$$\frac{1}{R_g} = \frac{k_g A_a}{\sigma\sqrt{2\pi}}\int_0^{\infty} \frac{\exp[-(\Upsilon/\sigma - t/\sigma)^2/2]}{[t/\sigma + M]}\,d(t/\sigma) \tag{32}$$

where

$$M = \frac{\alpha B\Lambda_o}{\sigma}(\frac{T}{T_o})(\frac{P_{go}}{P_g}) \tag{33}$$

Recognizing that, $h_g = \frac{1}{R_g A_a}$ and, $\frac{h_g\sigma}{k_s} = C_g$ allows the gap integrals to be written in a completely non-dimensional form

$$C_g = K.\frac{1}{\sqrt{2\pi}}\int_0^{\infty} \frac{\exp[-(\Upsilon/\sigma - t/\sigma)^2/2]}{[t/\sigma + M]}\,d(t/\sigma) \tag{34}$$

where

$$M = \frac{\alpha B\Lambda_o}{\sigma}(\frac{T}{T_o})(\frac{P_{go}}{P_g}) \tag{35}$$

or

$$M = \alpha\,\frac{(\gamma - 1)}{(\gamma + 1)}\sqrt{\frac{2\pi}{R_o}}\,\frac{\sqrt{MT}}{P_g}\,k_g \tag{36}$$

At this point it is suggested that numerical integration of equation (34) be avoided for small values of M. A transformed version of the above expression was developed for use when M < 2.50 and is presented here directly.

$$C_g = K\,\frac{e^{-c^2}}{\sqrt{2}}\left\{\int_0^{c} e^{s^2}[1 + \mathrm{erf}(s - M/\sqrt{2})]\,ds + \frac{E1(M^2/2)}{2\sqrt{\pi}}\right\} \tag{37}$$

where

$$c = (Y/\sigma + M)/\sqrt{2} \qquad (38)$$

and El is the exponential integral defined as:

$$El(z) = \int_z^{\infty} \frac{e^{-t}}{t}\, dt \quad (/\arg z/< \pi) \qquad (39)$$

For large values of M, indicative of near vacuum conditions, the original expressions can be integrated safely.

Table 1 Non-dimensional Gap Conductance C_g/K versus Relative Separation Y/σ

	Y/σ											
M	2.00	2.20	2.40	2.60	2.80	3.00	3.20	3.40	3.60	3.80	4.00	M
0.010	0.8072	0.6891	0.5921	0.5142	0.4524	0.4036	0.3650	0.3340	0.3087	0.2877	0.2699	0.010
0.020	0.7638	0.6594	0.5724	0.5014	0.4443	0.3985	0.3616	0.3318	0.3072	0.2866	0.2690	0.020
0.030	0.7365	0.6405	0.5595	0.4928	0.4386	0.3946	0.3590	0.3299	0.3058	0.2855	0.2681	0.030
0.040	0.7160	0.6260	0.5495	0.4860	0.4339	0.3914	0.3568	0.3283	0.3045	0.2845	0.2673	0.040
0.050	0.6992	0.6140	0.5411	0.4801	0.4298	0.3886	0.3547	0.3267	0.3033	0.2835	0.2665	0.050
0.060	0.6850	0.6037	0.5338	0.4749	0.4261	0.3859	0.3527	0.3252	0.3021	0.2825	0.2657	0.060
0.070	0.6724	0.5945	0.5271	0.4702	0.4227	0.3834	0.3509	0.3238	0.3010	0.2816	0.2649	0.070
0.080	0.6611	0.5862	0.5211	0.4658	0.4195	0.3811	0.3491	0.3224	0.2999	0.2807	0.2641	0.080
0.090	0.6509	0.5786	0.5155	0.4617	0.4165	0.3788	0.3474	0.3210	0.2988	0.2797	0.2633	0.090
0.100	0.6414	0.5715	0.5103	0.4578	0.4136	0.3766	0.3457	0.3197	0.2977	0.2788	0.2625	0.100
0.200	0.5719	0.5180	0.4694	0.4266	0.3896	0.3579	0.3308	0.3075	0.2876	0.2702	0.2550	0.200
0.300	0.5247	0.4802	0.4393	0.4026	0.3703	0.3422	0.3179	0.2968	0.2784	0.2623	0.2481	0.300
0.400	0.4881	0.4501	0.4147	0.3825	0.3538	0.3285	0.3064	0.2870	0.2699	0.2549	0.2416	0.400
0.500	0.4580	0.4250	0.3938	0.3651	0.3392	0.3162	0.2959	0.2779	0.2621	0.2480	0.2354	0.500
0.600	0.4325	0.4033	0.3755	0.3496	0.3261	0.3051	0.2863	0.2696	0.2547	0.2415	0.2296	0.600
0.700	0.4103	0.3843	0.3592	0.3357	0.3142	0.2948	0.2774	0.2618	0.2478	0.2354	0.2241	0.700
0.800	0.3907	0.3674	0.3446	0.3231	0.3033	0.2853	0.2691	0.2545	0.2414	0.2296	0.2189	0.800
0.900	0.3733	0.3521	0.3314	0.3116	0.2933	0.2765	0.2613	0.2476	0.2352	0.2241	0.2139	0.900
1.000	0.3576	0.3383	0.3192	0.3010	0.2840	0.2683	0.2541	0.2412	0.2295	0.2188	0.2092	1.000

Example Calculation

This example is taken from reference 4 with the original experimental data taken from J.J. Henry, reference 5.

Solids: Stainless Steel 416 Pair

$k_1 = k_2 = 25.26$ W/m°K

$\therefore\ k_s = 25.26$ W/m°K

$H_1 = H_2 = 3.80 \times 10^{10}$ Pa

$\sigma_1 = 3.81$ μm, $\sigma_2 = 1.57$ μm

$\therefore\ \sigma = 4.12$ μm

Fluid : Air at 377°K and one atmosphere

Using the slip development:

$k_g = 0.0298$ W/m°K, $\therefore K = 1.18 \times 10^{-3}$

Assume $\alpha_1 = \alpha_2 = 0.9$, $\therefore \alpha = 2.44$

$B = 1.64$

$\Lambda_o = 6.40 \times 10^{-8}$m, $\therefore \frac{\Lambda_o}{\sigma} = 1.55 \times 10^{-2}$

$(\frac{T}{T_o}) = 1.31$, $(\frac{P_{go}}{P_g}) = 1.0$

$$M = \frac{\alpha B \Lambda_o}{\sigma} (\frac{T}{T_o})(\frac{P_{go}}{P_g}) = 0.081$$

Using the transition development:

$\alpha = 2.44$, $\gamma = 1.40$, $\sqrt{\frac{R_o}{2\pi}} = 36.38$

$k_g = 0.0298$ W/m°K, $P_g = 1.013 \times 10^5$Pa

$\sigma = 4.12$ μm, $\mathcal{M} = 28.97$

$$M = \alpha\frac{(\gamma - 1)}{(\gamma + 1)} \sqrt{\frac{2\pi}{R_o}}\, \frac{\sqrt{\mathcal{M}T}}{P_g}\, \frac{k_g}{\sigma} = 0.083$$

Integrating expression (37) using the following inputs: $p/H = 21.6 \times 10^{-4}$, gives a separation of $Y/\sigma = 2.85$. Also

$K = 1.18 \times 10^{-3}$, $M = 0.082$ which

results in:

$$C_g = \frac{h_g \sigma}{k_s} = 4.82 \times 10^{-4}$$

$$\therefore\ h_g = 2.96 \times 10^3 \text{ W/m}^{2}\text{°K}$$

J.J. Henry reports a value of non-dimensional joint conductance, $C_j = 9.25 \times 10^{-4}$, and a value of non-dimensional contact conductance, $C_c = 4.79 \times 10^{-4}$. Subtracting these two values will give the experimentally determined gap conductance as follows:

$$C_g = C_j - C_c$$

$$\therefore\ C_g = 4.46 \times 10^{-4}$$

Comparing this measured value to the calculated conductance gives an error of $\frac{|4.46 - 4.82|}{4.46} \times 100 = 8.1\%$ in this particular case.

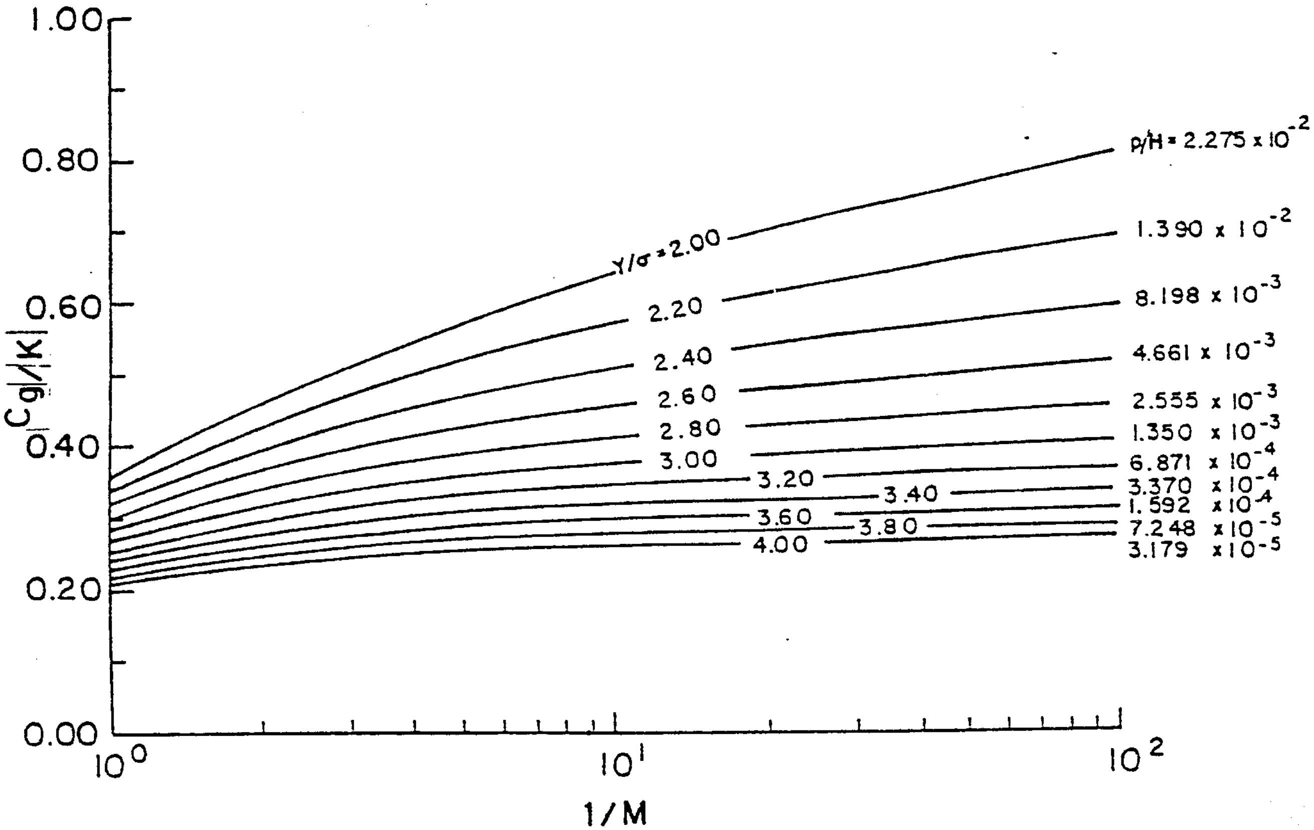

Fig. 7 Graph of C_g/K versus 1/M for $2.0 \le Y/\sigma \le 4.0$

A table of C_g/K for $0.01 \le M \le 1.0$ with separations of $2.00 \le Y/\sigma \le 4.00$ is included for ease of calculation. This data is also available in graphical form in Fig. 7. The range of M plotted covers most common gases, surface roughnesses, interface temperatures, and gas conductivities found near atmospheric pressure.

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