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Thermal Gap Conductance of Conforming Surfaces in Contact, Part I: Theory

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ABSTRACT

Heat transfer through gas layers of contact interfaces formed by two microscopically rough surfaces is studied. Rarefied gas conduction between smooth parallel plates is examined with data obtained from the literature. Two important dimensionless parameters are introduced; one representing the ratio of the rarefied gas resistance to the continuum gas resistance, and the other representing gas rarefaction effects. Effects of gas rarefaction and surface roughness are studied in relation with the parallel plates case. It is proposed that the effective gap thickness at light loads may be estimated by a roughness parameter, the maximum peak height R_p. The comparison between the theory and the measured values of gap conductance for the light loads shows excellent agreement.

KEYWORDS

gap conductance, contact interface, contact resistance

NOMENCLATURE

A_a	apparent area of contact
CLA	centerline average surface roughness
d	gap thickness
G	dimensionless gap resistance, $G = \frac{k_g}{h_g d}$
h	conductance, $h = \frac{Q/A_a}{\Delta T}$
Kn	Knudsen number, Λ/d
k_g	thermal conductivity of gas
L	sample trace length
M	gas parameter, $(\frac{2-TAC_1}{TAC_1} + \frac{2-TAC_2}{TAC_2})\beta\Lambda$
M^*	gas rarefaction parameter, M/d
P_g	gas pressure
Pr	Prandtl number, $c_p\mu/k$
R_p	maximum peak height
TAC	thermal accommodation coefficient
ΔT	effective temperature difference across interface, $T_1 - T_2$
t	local gap thickness
Q	heat transfer rate
q	heat flux, Q/A_a
Y	mean plane separation, effective gap thickness

Greek Symbols

β	$\beta = \frac{2\gamma}{\gamma+1}\frac{1}{Pr}$
γ	ratio of specific heats, c_p/c_v
δ	effective gap thickness
Λ	molecular mean free path
σ	rms surface roughness

Subscripts

1, 2	surfaces 1 and 2
c	contact
FM	free molecular
g	gap
j	joint

1 INTRODUCTION

Heat transfer through interfaces formed by the mechanical contact of two solids has many important applications such as in heat exchangers, microelectronic-chip cooling, and nuclear fuel-temperature control. One of the fundamental (and perhaps most important) studies in contact heat transfer involves the contact of two surfaces which are flat but microscopically rough.

Typically heat transfer through contact interfaces is associated with the presence of interstitial gases/fluids. Under such conditions, the rate of heat transfer across the interfaces depends upon a number of parameters: thermal properties of solids and gases/fluids, surface roughness characteristics, applied mechanical load and microhardness characteristics of solids, etc. Because of the large number of involved parameters, numerous attempts by various researchers to model the thermal gap conductance have not been completely successful. While analytical models tend to neglect some of the important parameters, experimental correlations are valid only for limited ranges of these parameters (Shlykov, [1]; Veziroglu, [2]; and Rapier, Jones and McIntosh, [3]). Often, the disagreement between the measured and predicted values of the conductance is found to be in the order of the magnitude of the experimental values.

In the present paper various effects on the gap heat transfer are examined, and an accurate model (Yovanovich, DeVaal and Hegazy, [4]) to predict the gap conductance along with an important surface roughness parameter to predict the effective gap thickness are presented. The accuracy of the model has been experimentally verified in an accompanying paper (Song and Yovanovich, [5]).

2 REVIEW OF CONTACT INTERFACE HEAT TRANSFER

2.1 Conductance Definitions

Heat transfer through interfaces formed by the contact of two nominally-flat surfaces, when radiation effects are neglected, takes the following form:

$$Q_j = Q_c + Q_g \tag{1}$$

where Q_c, Q_g, Q_j are the rates of heat transfer through the solid contact spots, through the interstitial gas layer, and the total rate of heat transfer, respectively. The conductance is introduced in the same manner as the film coefficient in convective heat transfer:

$$h = \frac{Q/A_a}{\Delta T}$$

where h is the conductance, ΔT is the effective temperature difference across the interface, and A_a is the apparent contact area.

2.2 Gap Conductance

The earliest and the simplest form of the gap conductance models (Cetinkale and Fishenden, [6]; Fenech and Rohsenow, [7]; Laming, [8]; Shlykov and Ganin, [9]) assumes that the contact interface gap may be represented by two parallel plates separated by an effective gap thickness δ. The gap conductance h_g is modelled as:

$$h_g = \frac{k_g}{\delta} \tag{2}$$

where the effective gap thickness, δ, depends upon the roughness characteristics of the two surfaces, the contact pressure and the microhardness. These models however ignore the effect of the contact pressure upon the gap thickness. The effective gap thickness δ is estimated by correlating the gap conductance measurements in terms of the surface roughness, typically the sum of the centerline averages (CLA) of the two surfaces.

The magnitude of the effective gap thickness of contact interfaces is typically of the range $0.1 < \delta < 100\ \mu m$. When the physical size of the gas layer, through which the gas conduction takes places, is comparable to the level of the gas molecular movement the continuum assumption of the gas medium is no longer valid. This effect is commonly referred to as 'rarefied gas' heat conduction.

This effect results in retardation of the heat transfer, and is often modelled in the form of a distance serially added to the physical heat flow path (Henry, [10]; Veziroglu, [2]; and Yovanovich, [11]):

$$h_g = \frac{k_g}{\delta + M} \tag{3}$$

The gas parameter, M, depends upon the gas type, gas pressure and temperature, and the thermal accommodation coefficient (a measure of the energy exchange between the gas molecules and the solid surfaces). This parameter, which will be discussed in detail in Section 3, can vary in the order of the magnitude of the effective gap thickness, δ.

The manner in which the gas rarefaction effect is modelled has not been agreed upon, as there appears to be a number of different approaches (Rapier et al., [3]; Lloyd et al., [12]; Garnier and Begej, [13]; Mentes et al., [14]; and Loyalka, [15]). Furthermore, it is difficult to obtain an accurate estimate of the thermal accommodation coefficient (TAC) which is a parameter of critical importance in rarefied gas heat transfer. Most of the authors involved with contact interface gap heat transfer research have relied upon TAC measurements obtained in environments much different from the contact situations, and these estimates within themselves showed a great deal of uncertainties. There appears to be no previous serious effort taken to estimate TAC directly within the environment of the contact interface heat transfer.

Instead of making the parallel-plates assumptions (Eq. 2 and 3), several authors (Shvets and Dyban, [16]; Shlykov, [1]; Popov and Kransnoborod'ko, [17]) took an approach of representing the geometry of the interface gap by correlating the surface height distributions obtained from several machined and ground surfaces. Dutkiewicz [18] took a statistical approach by assuming that the roughness heights of the contact surfaces are distributed according to the Gaussian model, and presented tabulated results for the gap conductance predictions (with some restriction in the range of the surface height distributions).

Yovanovich, DeVaal and Hegazy [4], also assuming Gaussian distribution of the surface height, developed a gap conductance model in an integral form. In this model the effect on the deformation of the gap due to the contact pressure is taken into consideration. The development of the model is presented (briefly) here since this model is later modified and used extensively in the present work.

The integral model for the gap conductance, which is denoted in the present work as the YIGC (Yovanovich Integral Gap Conductance) model, takes into consideration the variation in the local gap thickness due to the surface roughness. The model assumes that the temperatures of the two surfaces in contact are uniform at T_1 and T_2, and the entire interface gap consists of many elemental flux tubes of different thermal resistance. The resistances of these elemental flux tubes are then connected in parallel to result in the overall gap conductance in an integral form:

$$h_g = \frac{k_g}{\sqrt{2\pi}\sigma} \int_0^\infty \frac{exp[-(Y/\sigma - t/\sigma)^2/2]}{(t+M)/\sigma} d(t/\sigma) \tag{4}$$

where t = length of the elemental flux tube or the local gap thickness

M = gas parameter to be discussed in Section 3

k_g = thermal conductivity of the gas

Y = mean plane separation distance or effective gap thickness

The term, $t + M$, may be regarded as the effective heat flow distance of the local elemental flux tube.

3 RAREFIED GAS HEAT TRANSFER BETWEEN PARALLEL PLATES

Gas conduction in the contact interface is a complex phenomenon mainly due to the statistical nature of the gap geometry. In addition, the uncertainty associated with the present understanding of rarefied gas heat transfer, which arises from the small size (comparable to the gas molecular movement level) of the gap thickness, makes it difficult to accurately model the gap gas heat transfer. Here, the case of the rarefied gas conduction between two smooth parallel plates is considered, and the accuracy of a simple, parallel-plate, heat transfer model, which numerous researchers have incorporated into their contact interface gap conductance models, is verified with experimental data. The contact interface gap conductance may then be examined in relation with the parallel-plate case. During this analysis, a pair of important dimensionless parameters will be introduced.

3.1 Heat-Flow Regimes

Conduction heat transfer through a gas layer between two non-contacting parallel plates is commonly classified into four heat-flow regimes; continuum, temperature-jump, transition, and free-molecular (Springer, [19]). A convenient parameter which characterizes the regimes is the Knudsen number defined as:

$$Kn = \frac{\Lambda}{d} \tag{5}$$

where Λ is the molecular mean free path and d is the distance separating the two plates.

In the continuum regime ($Kn \ll 1$), the heat transfer between the plates takes place mainly through the collisions of the gas molecules. The rate of heat transfer in this regime is independent of the gas pressure, but varies with the gas temperature. Fourier's law of conduction can be used in this regime.

As the gas pressure is reduced, the intermolecular collisions become less frequent, and the exchange of energy between gas molecules and the plates starts to affect the heat transfer rate between the plates. Typically characterized by the Knudsen number range of $0.01 < Kn < 0.1$, the heat flow under this condition exhibits a 'temperature-jump' behavior (Kennard, [20]). In this regime, the exchange of energy between the gas molecules and the plate wall is incomplete, and, as a result, a 'discontinuity' of temperature develops at the wall-gas interface.

At the extreme end of very low gas pressure (or high gas temperature), intermolecular collisions are rare, and the essential mechanism of heat transfer in this regime is the exchange of energy between gas molecules and the plates. This heat-flow regime, typically with $Kn > 10$, is called the 'free-molecular regime'.

Between the temperature-jump and the free-molecular regimes is the 'transition regime', in which intermolecular collisions and the energy exchange between the gas molecules and the plate walls are both important. The Knudsen number range for this regime is typically $0.1 < Kn < 10$.

3.2 Simple Kinetic Theory Models

For the temperature-jump and the free molecular heat-flow regimes, there exist simple models for heat transfer through gases between two parallel isothermal plates. Theses models assume that the gas molecules are in thermal equilibrium and obey Maxwell's velocity distribution law. The heat transfer rate is modelled in terms of the gas molecular mean free path, and thus these models are sometimes referred to as 'mean free path models'.

When Maxwell's theory for temperature-jump distance is employed, the gas conduction between two parallel plates for the temperature-jump regime may be modelled as (Kennard, [20]):

$$q = \frac{k_g}{d + M}(T_1 - T_2) \tag{6}$$

where T_1 and T_2 are the uniform temperatures of the two plates, and q is the heat flux. The gas parameter, M, is defined as:

$$M = \left(\frac{2 - TAC_1}{TAC_1} + \frac{2 - TAC_2}{TAC_2}\right)\left(\frac{2\gamma}{\gamma + 1}\right)\left(\frac{1}{Pr}\right)\Lambda \tag{7}$$

where TAC_1, TAC_2 = thermal accommodation coefficients corresponding to the gas-solid combination of plates 1 and 2, respectively

γ = ratio of specific heats

Pr = Prandtl number

Λ = molecular mean free path

Thermal accommodation coefficient (TAC) depends upon the type of the gas-solid combination, and is, in general, very sensitive to the condition of the solid surface. It represents the degree to which the kinetic energy of a gas molecule is exchanged while in collision with the solid wall.

The gas parameter, M, which has the unit of length, represents in Eq. 6 the temperature-jump distances for the two plates. It is of the order of the gas mean free path, which in turn varies proportionally with the gas temperature and inversely with the gas pressure (Λ is inversely proportional to P_g).

The heat flow in the free-molecular regime was modelled by Knudsen (Kennard, [20]):

$$q_{FM} = \frac{k_g}{M}(T_1 - T_2) \tag{8}$$

It is observed from this model that the heat flow in the free-molecular regime is independent of the distance separating the two plates. Furthermore, the heat flux q_{FM} is inversely proportional to M and thus is directly proportional to the gas pressure.

The heat-transfer mechanism of the transition regime is very complex, and there is no simple theory for this regime.

3.3 Interpolated Simple Kinetic Theory Model

Yovanovich [11], in developing his approximate expression for h_g (Eq. 3), assumed that Eq. 6 effectively represents the heat transfer for all four flow regimes. This assumption seems reasonable since for the continuum regime the gas parameter, M, is negligibly small compared to d, and as the Knudsen number increases M begins to affect the term $\frac{k_g}{d+M}$. In the free-molecular regime, Eq. 6 effectively reduces to the free-molecular model, Eq. 8.

Various other researchers, in developing models for the gap conductance, have assumed this interpolated form for the rarefied-gas heat transfer. In the present work, Eq. 6 is referred to as the interpolated simple kinetic theory (ISKT) model. It will be seen in the following sections that this model provides an accurate representation of heat transfer for all conduction regimes of the parallel-plate configuration.

3.4 Comparison of ISKT Model with Experimental Data

The ISKT model (Eq. 6) may be written in terms of two dimensionless parameters as:

$$G = M^* + 1 \tag{9}$$

where

$$G = \frac{k_g}{h_g d} \quad \text{and} \quad M^* = \frac{M}{d}$$

The dimensionless resistance, G, may be interpreted as the ratio of the rarefied gas resistance to the continuum resistance. The dimensionless parameter, M^*, represents the degree of gas rarefaction, and accordingly it is here referred to as the rarefaction parameter. It is important to note that all experimental data which are discussed in this section essentially form one curve when normalized to these parameters.

Teagan and Springer [21] made measurements of heat transfer between parallel plates using argon ($0.06 \leq Kn \leq 5$) and nitrogen ($0.03 \leq Kn \leq 0.5$). Two aluminum plates of 25.4 cm diameter were used with the gap distance of 0.13 cm separating them. Braun and Frohn [22], [23] used stainless steel plates of 27.5 cm diameter and 1 cm gap spacing to measure the heat transfer through helium and argon. The Knudsen number range covered for the helium measurements was $10^{-4} \leq Kn \leq 2$ and for the argon, $10^{-4} \leq Kn \leq 1$.

Figure 1 shows the measured values of G in comparison with the predicted values of the ISKT model (Teagan and Springer reported their measurements in the form of Q/Q_{FM} against $1/Kn$, and Braun and Frohn, $Q/Q_{continuum}$ against $1/Kn$). It is seen from the figure that, for the wide range (nearly five orders of magnitude) of M^* covered by these authors, the agreement between the predicted values of G and the measurements is excellent. It is important to observe that the ISKT model is also valid for the transition regime.

Two major conclusions, concerning the rarefied-gas heat transfer between parallel plates, may be drawn as a result of the preceded study:

- The ISKT model accurately predicts the heat flow rate for all conduction regimes.
- The heat flow rate, when normalized to G (dimensionless resistance), depends upon one parameter, M^* (rarefaction parameter).

4 CONTACT INTERFACE GAP HEAT TRANSFER

4.1 Effect of Surface Roughness on Gap Conductance

Rarefied gas conduction between parallel plates may be considered as the limiting case of the contact interface gas conduction as the surface roughness diminishes. The degree of the roughness effect upon the gap conductance has not been clearly understood. The integral gap conductance model (YIGC) provides excellent description of the effect due to the surface roughness.

The YIGC model may be written for the dimensionless resistance, G, in terms of the rarefaction parameter, M^*, as:

$$G = \frac{k_g}{h_g Y} = \frac{\sqrt{2\pi}}{\int_0^\infty \frac{exp\left[-\left(Y/\sigma - t/\sigma\right)^2/2\right]}{(t/\sigma)/(Y/\sigma) + M^*} d(t/\sigma)} \tag{10}$$

where G and M^* are defined in Eq. 9 with d replaced by the effective gap thickness Y.

The dimensionless resistance G, according to the YIGC model, depends on two parameters, M^* and Y/σ:

$$G = G(M^*, Y/\sigma) \tag{11}$$

As discussed in the previous section, the parameter M^* accounts for the gas rarefaction effect, and it is independent of surface roughness. According to the YIGC model, the surface roughness effect appears in the form of the ratio of the effective gap thickness to the rms roughness.

Figure 2 shows, in terms of the parameters, G and M^*, the YIGC model (Eq. 10) along with the ISKT model (Eq. 9) of the parallel-plates gas conduction. The YIGC and ISKT models are essentially equivalent for the region of large M^* ($M^* > 1$), and also for smooth surfaces (large Y/σ). The parallel plates may be considered to be associated with negligible surface roughness, and thus the corresponding Y/σ value would be very large. Therefore, lower G values of YIGC model (compared to those of ISKT) may be interpreted to be due to the surface roughness effect. The surface roughness effect is significant only in the region of small M^* ($M^* < 1$). Near the continuum regime (lower end of M^*) the surface roughness effect, for the normal range of Y/σ ($2.0 \leq Y/\sigma \leq 4.0$) is seen to produce about 40 percent enhancement in the gap conductance (compared to the perfectly smooth surface with the same effective gap thickness Y).

The gas rarefaction effect, which depends upon the rarefaction parameter M^* is shown as an increase in the dimensionless resistance G. For the range $M^* > 1$, the gap heat transfer does not appear to depend upon the surface roughness, and thus the gap conductance in this regime (and only in this regime) may be effectively estimated as:

$$h_g = \frac{k_g}{M+Y} \tag{12}$$

The analysis presented in this section based on the YIGC model reveals several important aspects of the gap conductance:

- The dimensionless gap resistance G represents the relative magnitude of the gap resistance in reference to the resistance associated with the gas layer (in the continuum conduction regime) between the parallel plates.

- The gap conductance, when normalized to G, is influenced by two effects; the gas rarefaction and the surface roughness. These effects are characterized by the dimensionless parameters M^* for the gas rarefaction and Y/σ for the surface roughness.

- In the region $M^* > 1$, the influence on the gap conductance of the surface roughness effect is negligible.

4.2 Simplified Expression for YIGC Model

Equation 10 is in an integral form, and its evaluation requires numerical integration. The integral was correlated by the first author to yield the following simple expression:

$$G(M^*, Y/\sigma) = f + M^* \tag{13}$$

where $f = 1 + \dfrac{0.304}{(Y/\sigma)(1+M^*)} - \dfrac{2.29}{[(Y/\sigma)(1+M^*)]^2}$

For the range $2.5 \leq Y/\sigma$ and $0.01 \leq M^*$, the maximum difference in G values computed by the simple expression and the integral model (Eq. 10) is about 2 percent. When M^* is very small (continuum regime), Eq. 13 becomes independent of M^* and reduces to:

$$G \simeq f' \tag{14}$$

where $f' = 1 + \frac{0.304}{Y/\sigma} - \frac{2.29}{(Y/\sigma)^2}$. This expression should be useful for applications where the interstitial fluid is liquid or grease.

5 EFFECTIVE GAP THICKNESS

A critical part of the gap conductance model is to accurately predict the effective gap thickness of the gas/fluid layer in the contact interface. This is a difficult task mainly because there are many parameters which influence the gap thickness; e.g. surface roughness characteristics, mechanical load and microhardness characteristics. Here the effective gap thickness is defined as the separation distance of the mean planes between two surfaces, and is given the symbol Y. The effective gap thickness Y increases with the surface roughness, and it decreases with increase in the mechanical load.

For the contact of a rough and a smooth surface under very light mechanical load, the effective gap thickness may be estimated as the maximum peak height of the rougher surface. The maximum peak height, R_p, is defined (Dagnall, [24]) as the height of the highest point of the profile above the mean line within the trace length L. The maximum peak height is an extreme value characteristic of the surface roughness, and thus, unlike other roughness parameters such as the rms height (σ) or the centerline average height (CLA), it depends upon the trace length (R_p increases with L). Therefore for an estimate of the effective gap thickness at light loads, R_p should be measured based on sufficiently long trace lengths.

The normalized value of the maximum peak height, R_p/σ, is of great interest in the present work, since it provides an estimate for the relative effective gap thickness (Y/σ) at light mechanical pressure. There appears to be a trend that R_p/σ of real surfaces in general decreases with increase in surface roughness (Rubert, [25], and Tsukada and Anno, [26]).

6 COMPARISON OF THEORY WITH EXPERIMENTAL RESULTS

Figure 3 shows the comparison of the theory of gap conductance with experimental results (Song, [27]) for specimen pairs of $\sigma = 1.53$ and 11.8 μm. These are the results of two extreme roughness specimen pairs. Experiments were performed on Stainless Steel 304 pairs and Nickel 200 pairs with helium, argon and nitrogen as the interstitial gas. The details of the experiments are provided in the accompanying paper (Song and Yovanovich, [5]).

The values of the thermal accommodation coefficient are estimated (Song [27]) as 0.55, 0.90 and 0.78 for helium, argon and nitrogen, respectively. The contact pressure was maintained at a very light level of 0.6 MPa for the Stainless Steel 304 pair and 0.4 MPa for the Nickel 200 pair. It may be noted that the relative maximum peak height R_p/σ for the roughest surface pair ($\sigma = 11.8$ μm) is 2.59, and for the lowest roughness pair ($\sigma = 1.53$ μm) is 3.63. These are the values used in the gap conductance predictions as Y/σ estimates.

It is observed that the results for each specimen pair, when normalized to G and M^*, form essentially single curve. In the rarefied-gas region of $M^* > 1$ the experimental results for both pairs are indistinguishable indicating that there is no appreciable effect due to surface roughness.

Near the continuum end of $M^* < 0.1$, the effect due to the surface roughness is distinctively exhibited for the very rough surface pair ($\sigma = 11.8\ \mu m$) as observed from the measured G values of about 0.8; this implies that the enhancement of the conductance due to the surface roughness when compared to the smooth parallel plates is about 25 percent. The predicted values of G are in excellent agreement with measurements; the maximum difference of about 20 percent occurs at the higher end of M^* where the measured values of h_g are less reliable due to the significant contribution of the contact conductance to the joint conductance.

7 SUMMARY

The accuracy of the simple model (ISKT) for predicting the rarefied-gas heat transfer between two smooth parallel plates was verified through available experimental data. Two important dimensionless parameters, G and M^*, were introduced. Using the existing gap conductance model (YIGC), two predominant effects on gap conductance, gas rarefaction and surface roughness, were discussed. For light load conditions it was proposed that the maximum peak height R_p may be used as the estimate for the effective gap thickness. The predicted values of gap conductance (YIGC theory with R_p as the estimate for Y) are in excellent agreement with the measured values under very light load conditions.

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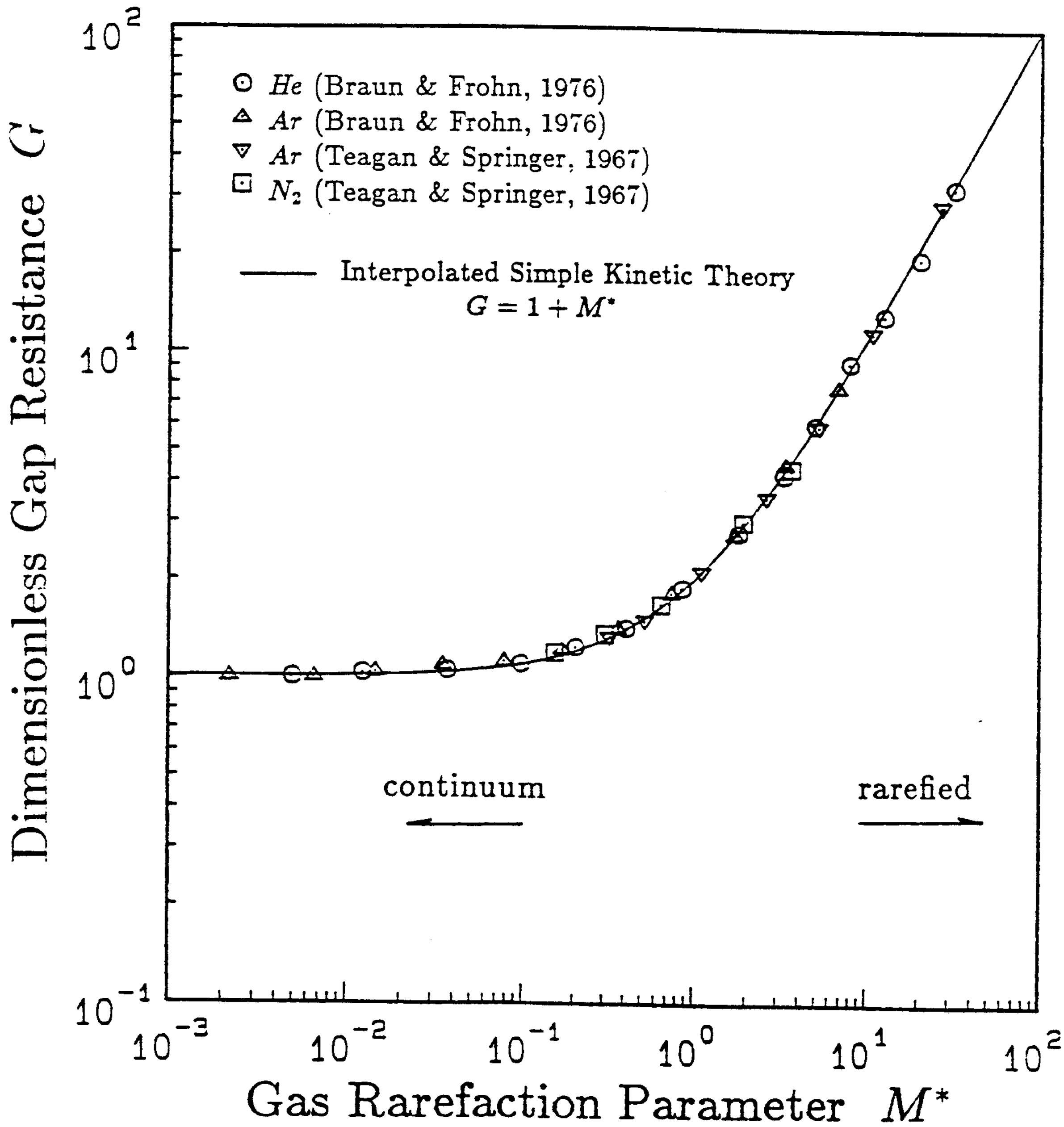

Figure 1: Comparison of ISKT Model with Experimental Data

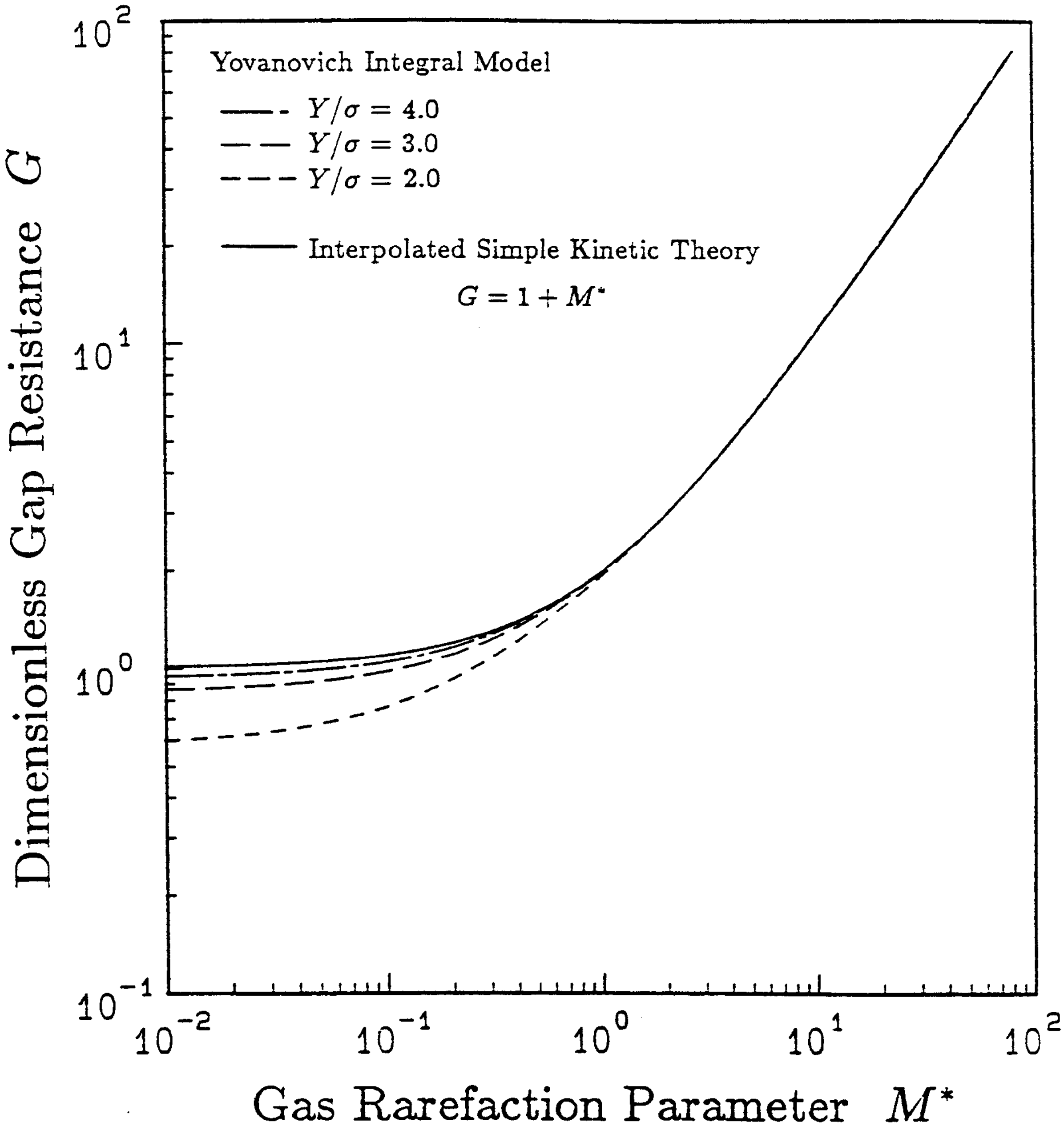

Figure 2: YIGC model in terms of G and M^*

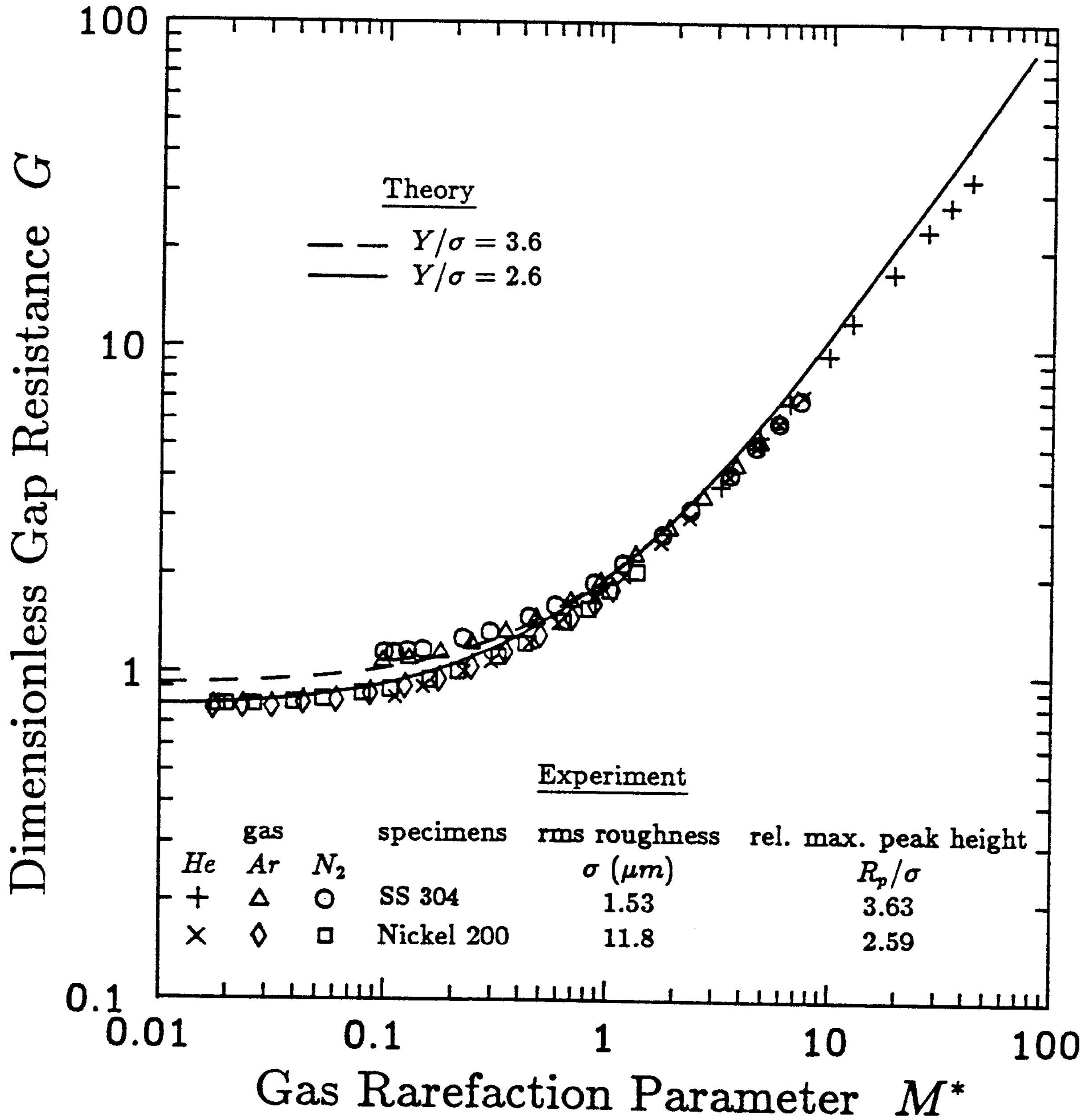

Figure 3: Comparison of Theory with Experiment