

CONTACT INTERFACE GAS HEAT TRANSFER: A METHOD OF MEASURING THERMAL ACCOMMODATION COEFFICIENT

by

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Abstract

An experimental method is proposed to estimate the thermal accommodation coefficient (TAC) values for given gas-solid combinations. The proposed method involves a series of heat transfer measurements of two solids in light contact with the interface gas pressure varied over a range. The method is simple to apply and yields accurate values of TAC. Experiments were performed to obtain TAC values for Helium, Argon and Nitrogen gases in the interfaces formed by the contact of Stainless Steel 304 pairs and Nickel 200 pairs. Estimated TAC values are 0.55, 0.90 and 0.78 for Helium, Argon and Nitrogen respectively.

Nomenclature

A_a	apparent area of contact
d	distance between two parallel plates
G	dimensionless gap resistance, $G = \frac{k_g}{h_g d}$
h	conductance coefficient, $h = \frac{Q/A_a}{\Delta T}$
Kn	Knudsen number, Λ/δ
k_g	thermal conductivity of gas
M	gas rarefaction parameter
P	contact pressure
P_g	gas pressure
P_0	reference pressure
Pr	Prandtl number
R_p	maximum peak height roughness
T_g	gas pressure
T_0	reference temperature
TAC	thermal accommodation coefficient
ΔT	effective temperature difference across interface
Q	heat transfer rate

Greek Symbols

α	$\alpha = 2 \left(\frac{2-TAC}{TAC} \right)$
β	$\beta = \frac{2\gamma}{\gamma+1} \frac{1}{Pr}$
γ	ratio of specific heats
δ	effective gap thickness
Λ	molecular mean free path
Λ_0	molecular mean free path at P_0 and T_0
σ	rms surface roughness

Subscripts

1, 2	surfaces 1 and 2
c	contact
g	gap
j	joint

I. Introduction

Often in applications of microelectronics heat transfer, contact interface contributes a significant resistance to the total heat flow path (Incropera 1988, Chu 1986). The mechanical contact pressure in these applications is typically low, and thus the heat transfer across the interface occurs mainly through the gas medium which exists in the interface gap.

Typical size of the interface gap is on the order of microns. Depending on the flatness and the roughness of the contacting surfaces, gap size may be even less than a micron. Gas heat conduction across such microscopically small gaps involves 'rarefied gas' phenomena (Kennard 1938), which effectively introduces additional thermal resistances to the usual Fourier-law based conduction calculations. There exists a number of theories and experimental correlations (Cetinkale and Fishenden 1951, Rapier et al. 1963, Shlykov 1965, Veziroglu 1967, Lloyd et al 1973, Garnier and Begej 1979, Loyalka 1982, Yovanovich et al. 1982) for predicting the contact interface gas conduction, in which the gas rarefaction effect is accounted for.

Most of these models assume, either explicitly or implicitly, the following expression:

$$h_g = \frac{k_g}{\delta + M} \quad (1)$$

where the gap conductance h_g is defined as

$$h_g \equiv \frac{Q_g/A_a}{\Delta T} \quad (2)$$

Q_g = heat flow rate through gas medium
 A_a = apparent area of contact
 ΔT = temperature difference across the interface

and k_g and δ are gas thermal conductivity and effective interface gap thickness. Gas rarefaction parameter, M , is written as:

$$M = \left(\frac{2 - TAC_1}{TAC_1} + \frac{2 - TAC_2}{TAC_2} \right) \left(\frac{2\gamma - 1}{\gamma + 1 Pr} \right) \left(\Lambda_0 \frac{T_g P_0}{T_0 P_g} \right) \quad (3)$$

where TAC_1, TAC_2 = thermal accommodation coefficient for contact surface 1 and 2
 γ = ratio of specific heats
 Pr = Prandtl number
 Λ_0 = molecular mean free path at reference pressure and temperature P_0 and T_0
 T_g = gas temperature
 P_g = gas pressure

Gas rarefaction parameter, M , has a unit of length, and may be considered as an extra distance the heat has to flow through in addition to the gap thickness δ . Depending on the type of the gas, the magnitude of M may be as large as 2 to 4 μm even at atmospheric gas pressure. Thus any attempt to ignore this parameter, in the interface heat transfer calculation, may result in a significant error, especially for light gases such as Helium or Hydrogen.

Thermal accommodation coefficient (TAC) represents the extent to which the exchange of energy takes place between the gas and the solid, and normally its value ranges between 0 and 1 depending upon the type and the temperatures of the gas and the solid. TAC is extremely sensitive to the adsorption condition

of the solid surface. Because of this one may find, for a given gas-solid combination, a wide range of TAC values in the literature.

In the present paper, an experimental method is proposed to estimate TAC values. The method requires a relatively simple experimental set up, but provides accurate TAC estimates.

II. Proposed Method for TAC Estimate

First consider a case of two perfectly smooth parallel plates which are separated by the distance d (Fig. 1). The rarefied gas heat transfer between the two parallel plates is presently well understood in the sense that both analytical solutions (Liu and Lees, 1961, Springer, 1971, Bassanini, Cercignani and Pagani, 1967 and 1968) and experimental data (Teagan and Springer, 1968, Braun and Frohn, 1976 and 1977) are in excellent agreement. It can be shown (Song, 1988) that the following expression accurately approximates the heat transfer coefficient for the parallel plate configuration:

$$h_g = \frac{k_g}{d + M} \quad (4)$$

This simple expression provides an insight as to how the gas rarefaction influences the heat transfer across the parallel plates. For a specified gas type and its thermodynamic state (gas temperature and pressure) the rarefaction parameter M is a constant, and the effect of gas rarefaction on heat transfer coefficient h_g depends upon the magnitude of the separation distance d relative to M . It is observed from Eq.4 that as d decreases h_g approaches the asymptote k_g/M . In other words for fully rarefied situation ($d \ll M$), gas conduction heat transfer rate is independent of the separation distance d .

Heat transfer across the interface of two solids in contact (Fig. 2) involves two modes, in the absence of radiation heat transfer, namely solid conduction across the contacting spots and gas conduction across the interface gap. For the solid conduction across the contacting spots, a number of theoretical works and experimental verification already exist in the literature (review papers by Fletcher, 1988; Yovanovich, 1986). A parameter of great importance in the gas conduction across the interface gap is the effective gap thickness δ . The size of the effective gap δ is influenced by various geometric and mechanical (Yovanovich, DeVaal and Hegazy, 1982; Song, 1988), namely:

- geometric - waviness and roughness of the surfaces
- mechanical - load pressure, microhardness of the solids

Accurate modelling of the gap thickness δ is a difficult task. However, if some estimate of δ is available, the gas heat conduction can be fairly accurately modelled by Eq. 1. This simple approximation is most accurate for smooth surfaces and for low mechanical contact pressure (Song, 1988).

To develop a method for estimating TAC, Eq. 1 may be rearranged to:

$$\frac{k_g}{h_g} = \delta + \alpha\beta\Lambda_0 \frac{T_g P_0}{T_0 P_g} \quad (5)$$

$$\text{where } \alpha = \frac{2-TAC_1}{TAC_1} + \frac{2-TAC_2}{TAC_2}$$

$$\beta = \frac{2\gamma - 1}{\gamma + 1 Pr}$$

For those applications where gas conduction contributes a significant portion of the total interface heat transfer, the difference between the two surface temperatures is in general small, so that it is reasonable not

to distinguish between TAC_1 and TAC_2 . Thus α may be assumed to depend upon an average value of TAC :

$$\alpha = 2 \left(\frac{2 - TAC}{TAC} \right) \quad (6)$$

It is seen from Eq. 5 that, for a given gas type (β and Λ_0) and for a controlled effective gap thickness (δ), the ratio k_g/h_g is linearly related to T_g and $1/P_g$ with α appearing as a slope. Therefore a series of contact interface measurements, where δ is held constant and the gas pressure P_g is varied over a wide range, would yield δ as the intercept and α as the slope. From α measurements TAC may be estimated by rearranging Eq. 6 as:

$$TAC = \frac{4}{\alpha + 2} \quad (7)$$

Above-outlined method for TAC estimates does not require any aprior knowledge of the size of the interface gap. However more accurate value of TAC can be obtained if a good estimate of interface gap (such as the maximum peak based model for light loads by Song (1988)) is available. Equation 5 may be expressed in terms of two dimensionless groups:

$$G = 1 + \alpha\beta Kn \quad (8)$$

where G = a dimensionless resistance, $\frac{k_g}{h_g\delta}$

and Kn = Knudsen number, $\frac{\Lambda_0 T_g P_0}{\delta T_0 P_g}$

The dimensionless resistance, G , may be interpreted as the ratio of the rarefied-gas resistance to the continuum resistance for the case of perfectly smooth parallel-plates configuration. Knudsen number, Kn , represents the extent to which the gas is rarefied. Thus under the continuum condition for the smooth parallel plates heat conduction, Kn is close to zero and G , in Eq. 8, becomes unity.

For the contact of real surfaces the effect of the surface roughness may be accounted for by modifying Eq. 8 as (Song (1988)):

$$G = G_{continuum} + \alpha\beta Kn \quad (9)$$

When this equation is compared with Eq. 8, it becomes obvious that the value of $G_{continuum}$ should approach unity as the surface roughness diminishes. The value of $G_{continuum}$ is always less than or equal to unity, and decreases with increase in the surface roughness.

Now, Eq. 9 may be applied in the same manner as Eq. 5 is used to obtain estimates of TAC. The advantage of using Eq. 9 is that for each data point one may observe Kn to identify its heat flow regime (continuum, temperature jump, transition, free molecular, Song (1988)), and apply an appropriate weighting scheme in the least-square estimate of α (or TAC).

The proposed method involves a series of heat transfer measurements of two solids in contact with the interface gas pressure varied over a range. It is difficult to directly measure only the gas conduction contribution of the total interface heat transfer. For a specified mechanical pressure level, however, the contribution due to the solid contact conduction may be estimated by a heat transfer measurement under a vacuum (at gas pressures lower than typically 0.01 torr). Thus the contribution due to gas conduction is obtained by subtracting the measurement under a vacuum from the total interface heat transfer rate:

$$Q_g = (Q_j)_{gas\ environment} - (Q_j)_{vacuum} \quad (10)$$

where Q_g = gas conduction contribution of interface heat transfer
 Q_j = total interface heat transfer

The contribution due to the solid contact conduction can be minimized by maintaining the mechanical pressure at the lightest possible level. For this reason we suggest that all gas interface measurement to be done at very light loads.

III. Experimental Details

Stainless Steel 304 and Nickel 200 materials were prepared to cylindrical samples of 2.5 *cm* diameter and 4.5 *cm* long. On each sample six 'T' type thermocouples were placed, and the temperature readings from the thermocouples yielded heat transfer rate and interface temperature difference. For each series of heat transfer measurements two samples were stacked vertically, and axial loads were applied by means of a diaphragm type air cylinder. For each sample pair, the contacting surface of the upper specimen was bead blasted and the surface of the lower specimen was lapped.

The test column was enclosed by a pyrex bell jar which could be evacuated to a vacuum level lower than 10^{-5} *torr*. The bell jar could also be filled with Helium, Argon or Nitrogen through a feed-through hole in the base plate. The gas pressure was monitored with a metal diaphragm type of pressure gauge. The heating element consisted of a copper block in which a pair of pencil-type cartridge heaters was embedded. Cooling was achieved by an aluminum cold plate where temperature controlled water was circulated. The test column was shielded with aluminum foil, and insulated with about 2 *cm* thick layer of Quartz Wool.

All tests in a gas environment were preceded by at least one measurement in a vacuum. The joint conductance h_j was obtained from the temperature measurements of the specimens according to its usual definition:

$$h_j = \frac{Q/A_a}{\Delta T} \quad (11)$$

The heat flow rate Q was taken as the average of the heat flow rates of the upper and lower specimens. The interface temperature difference ΔT was obtained from the difference in the extrapolated values of the interface temperature from the least-square fitted temperature distribution of the two specimens.

Four pairs of specimens with rms roughness ranging from 1.53 to 11.8 μm were tested. The mechanical contact pressure was maintained at about 0.5 *MPa*. By adjusting the the electrical power input to the heater elements, the contact temperature was controlled to about 170°C. During the experiment with each specimen pair, the gas pressure was varied from 10 to 700 *torr*. The ranges of experimental parameters are shown in Table 1. The combined rms roughness, σ , shown in the table is defined as:

$$\sigma = \sqrt{\sigma_1^2 + \sigma_2^2} \quad (12)$$

where σ_1 and σ_2 are the rms roughness of each specimen. The maximum peak height, R_p , of the bead blasted surfaces was also measured and this was used as a light-load estimate of the effective gap thickness δ .

IV. Experimental Results

Figures 3 through 6 show joint conductance measurements of all the experiments over a range of gas pressure. The measurements under vacuum are shown on the far left end of the plots. The vacuum measurements of h_j provide estimates of the solid contact conductance contribution in the gas environments. As mentioned previously the gap conductance may now be estimated as the difference in the joint conductance measurements between the gas environment and the vacuum.

It is seen in Fig. 3 that the gap conductance for all three gases contributes considerably higher than the solid contact conductance, even at gas pressures as low as 10 torr. For gas pressures lower than about 200 torr the joint conductance (or the gap conductance) measurements clearly exhibit the pressure dependence which attributes to the 'Rarefied Gas' phenomenon. As the gas pressure increases to about 400 torr the Argon and Nitrogen measurements level off, and this signifies the regime of near continuum gas conduction.

It should be mentioned that the authors decided, as an experimental guide line to maintain the interface temperature difference to be greater than 5 °C in order to minimize the uncertainty in the conductance estimates due to the thermocouple measurement error. This resulted in the restriction in the gas pressure range for the helium tests on stainless steel 304 specimens, since these tests for the gas pressure above about 100 torr required high heat flow rates and thus excessive temperature gradient axially across the specimen.

For rougher stainless steel specimens (Fig. 4, $\sigma = 4.83\mu\text{m}$), the regime of near continuum for argon and nitrogen is observed at lower gas pressure of about 200 torr. For very rough specimens (Fig. 6, $\sigma = 11.8\mu\text{m}$), the argon and nitrogen measurements exhibit a wide gas pressure range of near continuum regime. The helium measurements, as seen in Figs. 3 through 6, show gas pressure dependence even at near atmospheric pressure.

Least-square regressions were performed on the gap conductance measurements of Exp. #1 through #4 to obtain values of $G_{\text{continuum}}$ and α in accordance with Eq. 9. In reducing the gap conductance measurements and gas pressure and temperature to G and Kn , the maximum peak height R_p of the bead blasted surface was used as the estimate for δ (Song (1988)). The obtained values of $G_{\text{continuum}}$ and TAC for each experiment are given in Table 2.

The regression estimated values of TAC are in close agreement with each other, with the exception of Exp. #1. The TAC estimates for Exp. #1 appear to be consistently higher than those of other experiments. The regression estimated values of $G_{\text{continuum}}$ for Ar and N_2 are in close agreement between each other. Estimates of $G_{\text{continuum}}$ from He data are less reliable than those of Ar and N_2 since the heat flow regime for He is situated much further from the continuum conduction regime (towards rarefied-gas end) than that of Ar or N_2 . Those values of $G_{\text{continuum}}$ which are higher than unity may be attributed to underestimation of the roughness parameter R_p (the estimate of δ depends on R_p).

Figures 7 through 9 show $G - G_{\text{continuum}}$ values of He, Ar and N_2 for Exp. #2 through 4 over a range of Kn . Shown also are lines of Eq. 9 with graphically estimated values of TAC, along with the lines with the TAC values 0.05 higher and lower than the estimate. The graphically estimated values of TAC are:

for Helium	TAC =	0.55
Argon		0.90
Nitrogen		0.78

These values of TAC are preferred over the least-square fitted values because they appear to be more consistently in line with Eq. 9 over the Knudsen number ranges shown in Figs. 7 through 9. The general TAC correlation developed by Song and Yovanovich (1987) predicts the values of TAC for He, Ar and N_2 to be 0.30, 0.78 and 0.78, respectively. The predicted value for N_2 is in excellent agreement with the estimated

value. For *Ar*, the agreement is reasonable and well within the estimated uncertainty of the correlation which is about ± 25 percent. In the case of *He*, however, the correlation predicted value is significantly lower than the estimated value of 0.55. The values of TAC for *He*, which appear in the literature, may range from about 0.3 to 0.65. Table 3 gives the measured values obtained by various researchers of TAC.

V. Summary

An experimental method is proposed to estimate thermal accommodation coefficient which is an important parameter for gas conduction of interface contact heat transfer. The method is simple to apply and involves a relatively simple experimental set up. Experiments were performed for a number of stainless steel 304 and nickel 200 pairs over a range of surface roughness and gas pressure. TAC values for three different gases, namely Helium, Argon and Nitrogen were estimated for the gas temperature of about 170°C ; 0.55, 0.90 and 0.78 for *He*, *Ar* and *N₂*, respectively. Comparison of these values with those predicted by the TAC correlation of Song and Yovanovich (1987) shows good agreement for *Ar* and *N₂*. The estimated value for *He* is significantly higher than the correlation predicted value, but is well within the range of values found in the literature.

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Table 1: Ranges of Experimental Parameters

Parameters	Exp. #1	Exp. # 2	Exp. # 3	Exp. # 4
specimens	SS 304	SS 304	Ni 200	Ni 200
rms roughness σ (μm)	1.53	4.83	2.32	11.8
max. peak height R_p (μm)	5.55	14.7	8.61	30.6
gas pressure P_g (torr)	9.4 - 710.9	9.5 - 665.0	9.6 - 697.7	9.4 - 699.7
contact pressure P_c (MPa)	0.60 ± 0.02	0.47 ± 0.02	0.52 ± 0.02	0.38 ± 0.01
contact temperature T_c $^{\circ}\text{C}$	172 ± 4	168 ± 4	170 ± 3	172 ± 4

Table 2 : Least-Square Regression Estimate of TAC

		Exp. # 1	Exp. # 2	Exp. # 3	Exp. # 4
<i>He</i>	<i>TAC</i>	0.67	0.58	0.61	0.60
	<i>G_{cont}</i>	2.26	1.18	1.62	0.89
	<i>Kn</i>	0.39 - 3.8	0.19 - 1.6	0.043 - 2.9	0.011 - 0.76
<i>Ar</i>	<i>TAC</i>	0.96	0.88	0.93	0.87
	<i>G_{cont}</i>	1.13	0.98	1.07	0.79
	<i>Kn</i>	0.022 - 1.3	0.0080 - 0.55	0.015 - 0.88	0.0038 - 0.23
<i>N₂</i>	<i>TAC</i>	0.87	0.79	0.81	0.80
	<i>G_{cont}</i>	1.18	0.99	1.07	0.79
	<i>Kn</i>	0.020 - 1.4	0.0078 - 0.53	0.015 - 0.95	0.0035 - 0.26

Table 3 : Measured Values of TAC for *He* by Various Authors
(Saxena & Joshi, 1981)

Author(s)	Year	Surface	<i>T</i> (K)	TAC
Schäfer & Gerstacacker	1955	glass	384	0.365
Amdur & Guildner	1957	nickel	373	0.385
		platinum	374	0.368
		tungsten	373	0.470
Dickens	1954	platinum	296	0.51
Grilly, Taylor & Johnston	1946	platinum	380	0.54
Zimina	1972	silver	372	0.60
			572	0.65
Marek	1967	steel	373	0.393
Markowitz	1962	Zircaloy-2	458	0.327

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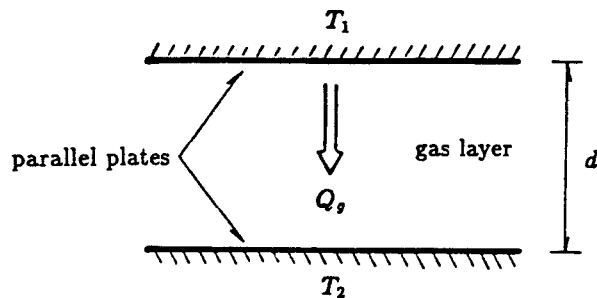


Figure 1 : Gas Conduction Between Smooth Parallel Plates

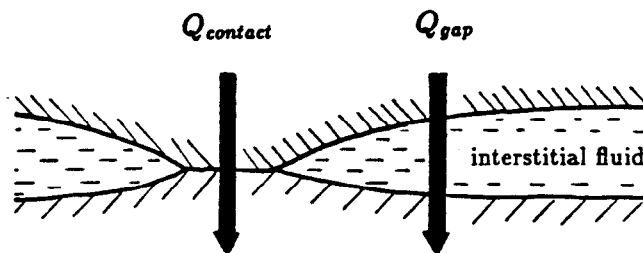


Figure 2 : Contact Interface Heat Transfer

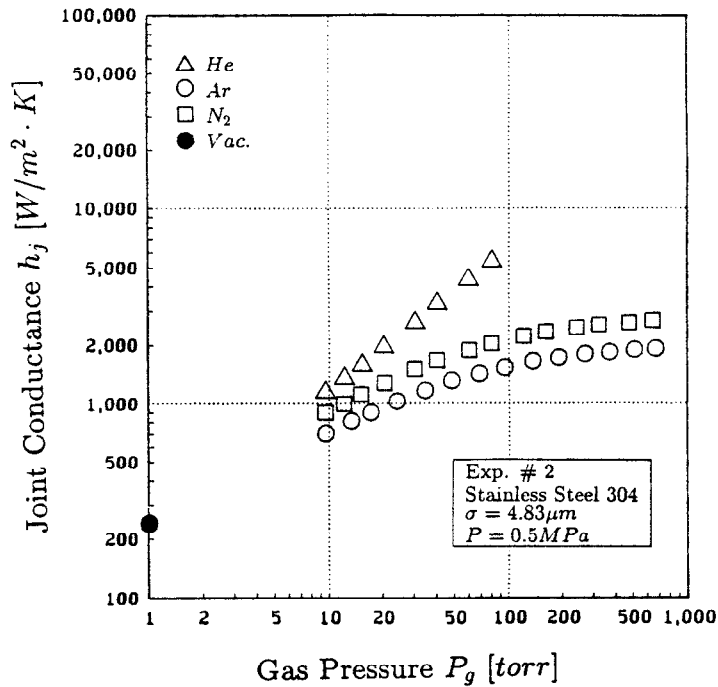
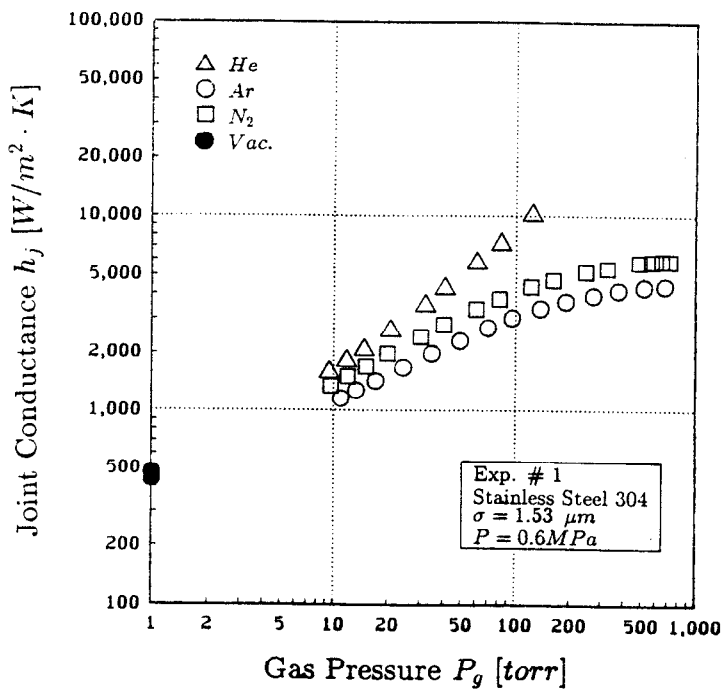


Figure 3 : Joint Conductance Measurements for Exp. # 1

Figure 4 : Joint Conductance Measurements for Exp. # 2

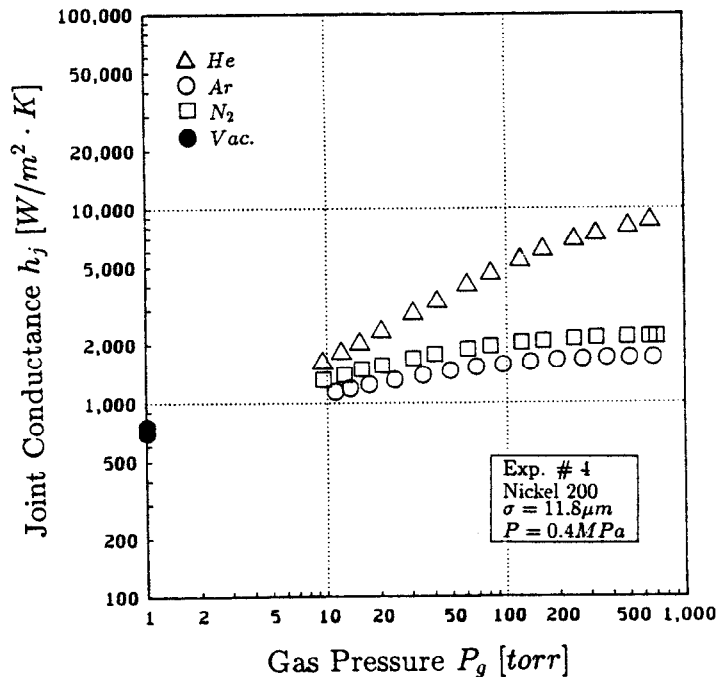
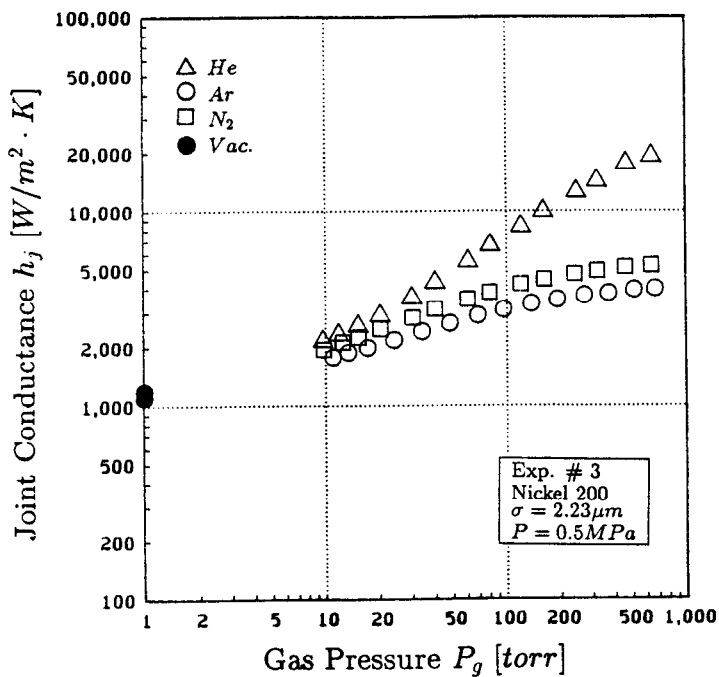


Figure 5 : Joint Conductance Measurements for Exp. # 3

Figure 6 : Joint Conductance Measurements for Exp. # 4

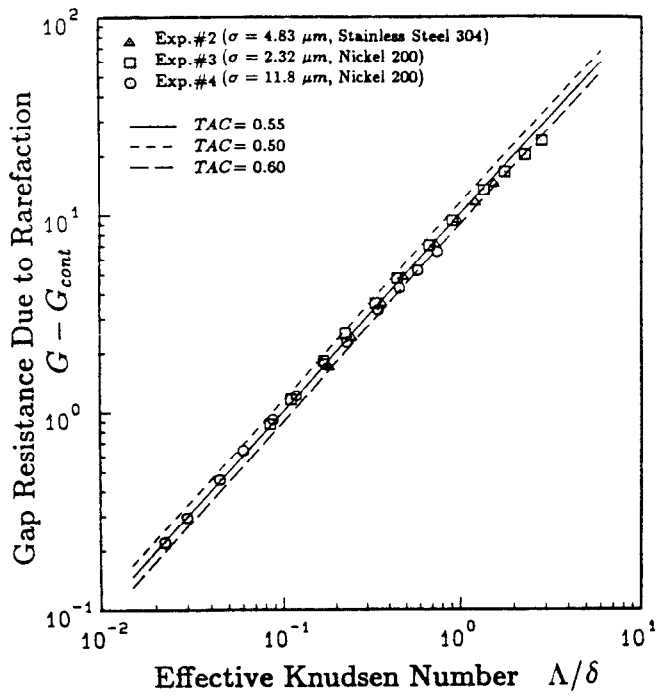


Figure 7 : TAC Estimate for Helium

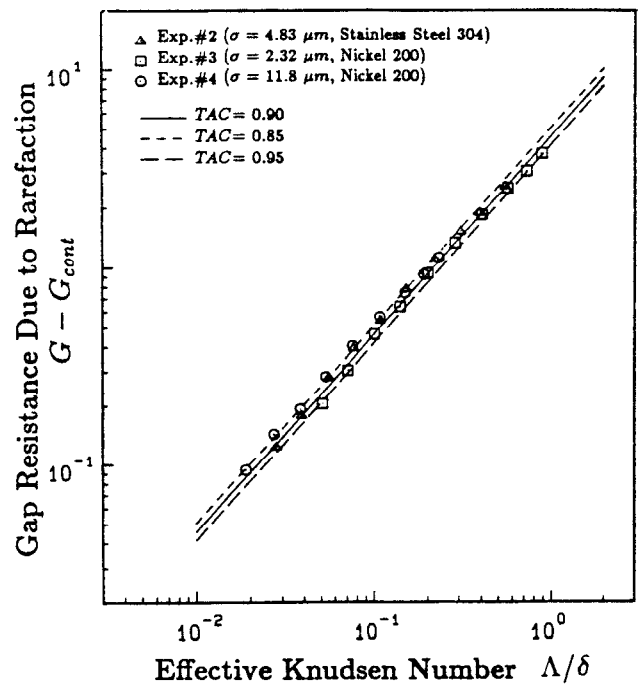


Figure 8 : TAC Estimate for Argon

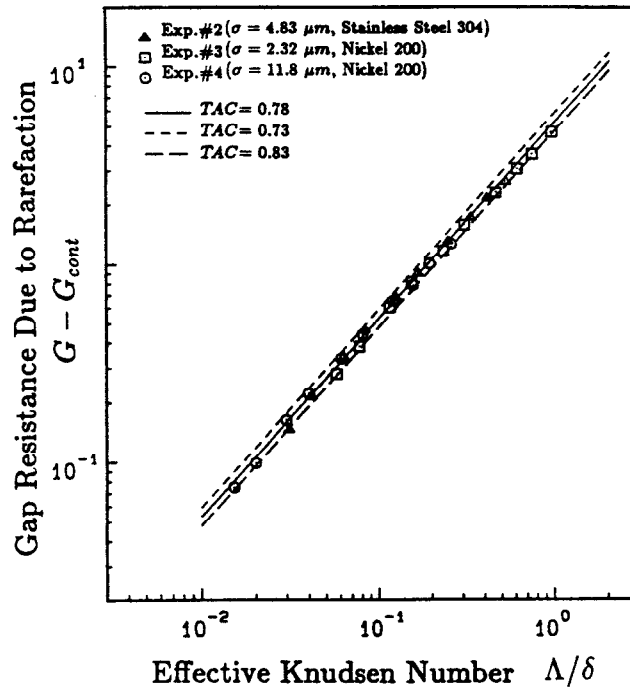


Figure 9 : TAC Estimate for Nitrogen