CORRELATION OF THERMAL ACCOMMODATION COEFFICIENT FOR 'ENGINEERING' SURFACES

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ABSTRACT

An expression for predicting thermal accommodation coefficient (TAC) of engineering surfaces is developed by correlating experimental data. The correlation is general and can be used for any combination of gases and solid surfaces for a wide temperature range. The correlation involves only those parameters which may be readily estimated. The surface-temperature dependence of TAC is embedded in the correlation and the asymptotic behavior of the correlation for the very high temperature region (2000 to 2500 K) is controlled by employing a well-known clean-surface TAC theory. The agreement between the predicted values of TAC and the experimental data is generally within 25 percent, which coincides with the scatter of the data.

NOMENCLATURE

C_0, C_1, C_2	constants in Eqs. 12, 13 and 14
D	constant in Eq. 8
E	energy of gas molecule
F	fractional coverage of adsorption layer
G	constant in Eq. 22
M	molecular weight
M^*	monatomic equivalent molecular weight
n	number of collisions
T	temperature
T_0	reference temperature

Greek Symbols

α	thermal accommodation coefficient (TAC)
α_∞	clean surface TAC
μ	ratio of molecular weights, $\frac{M_g}{M_s}$
$tan\theta$	mean asperity slope

Subscripts

a	adsorbed
c	clean
g	gas
i	incident
r	reflected

INTRODUCTION

The concept of thermal accommodation coefficient (TAC) dates back nearly nine decades when Smoluchowski(1898) introduced a constant to represent the extent to which the interchange of energy takes place by a stream of gas molecules striking a solid surface. Since then a considerable amount of effort has been spent by many researchers to measure, study and model TAC for various gases and solid surfaces. Extensive reviews on this subject are found in references (Hartnett, 1961, Wachman, 1962, Kaminsky, 1965, Goodman and Wachman, 1976, Goodman, 1980, Saxena and Joshi, 1981).

The value of TAC is very sensitive to the adsorption condition of the solid surface. For very light gases, such as Helium, the TAC value for a fully-adsorbed surface may be ten times greater than that of very 'clean' surfaces. Pioneering research efforts for measuring TAC for the period 1910–1940 (Soddy and Berry, 1909, Knudsen, 1911, Roberts, 1930, Michels, 1932) suffered from disagreements within their measurements mainly due to the failure to control the condition of the solid surfaces. It is only subsequent to the development of the experimental technique to maintain the condition of the surface nearly adsorption-free that consistent and predictable values of the TAC started to appear. To maintain an adsorption-free state, the solid surface is periodically heated to high temperature, typically to temperatures above 1000 or 2000 K to desorp the impurities from the surface. Furthermore, a technique called 'getter method', developed by the research group lead by L.B. Thomas(1980),

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is applied to collect any remaining impurities. Application of high-temperature heating methods is suitable only for refractory materials such as W, Mo, Ta and Pt, which have high melting temperatures. Because of this, most of the 'clean surface' data available are for W and Pt for a limited number of gases. A few other methods (see Goodman and Wachman, 1976) suitable for particular types of metal surfaces exist such as ion bombardment for Fe and vapor deposition method for Al, Be and alkali metal surfaces.

Typical engineering surfaces are far from such an idealized condition and would be fully covered by adsorption layers of unknown gas compositions. Thus, the experimental data and theories of TAC for 'clean' surfaces offer little use to those who are in need of TAC estimates for engineering surfaces. At present, there exists neither theory nor experimental correlation of a general form which can be readily used to estimate TAC for engineering surfaces. This is exemplified by the discrepancies in the values of TAC used by various researchers in gap conductance research (See Table 1). It is surprising that the values of TAC used for Helium range from 0.07 to 0.38. It should also be mentioned that often the surface-temperature dependence of TAC is neglected even for high temperature applications ($T > 500$ K).

In this paper, accounts are made for the development of a correlation for predicting TAC for engineering surfaces. The correlation is general and can be used for any combination of gases and solid surfaces. The correlation involves only those parameters that can be readily esimated.

DEFINITION OF TAC

Most commonly used definition of TAC is due to Knudsen(1911):

$$\alpha(T_s, T_i) = \frac{T_r - T_i}{T_s - T_i} \tag{1}$$

where T_r = temperature of reflected gas molecules
T_i = temperature of incident gas molecules
T_s = temperature of solid

This definition of TAC is sometimes referred to as 'nonequilibrium TAC' to distinguish it from the equilibrium TAC:

$$\alpha_{eq}(T) = \lim_{T_s \to T_i = T} \left(\frac{T_r - T_i}{T_s - T_i} \right) \tag{2}$$

Most of the measurements on TAC are based on either of the above two definitions. A third type of definition, which is more suitable for molecular beam type measurement of TAC, is:

$$\alpha_{energy} = \frac{E_r - E_i}{E_s - E_i} \tag{3}$$

where E_r = energy of reflected gas molecules
E_i = energy of incident gas molecules
E_s = energy of gas molecules corresponding to T_s

Table 1. Values of TAC used by various authors

Author(s)	Gas	Values (equation) used for TAC
Dharmadurai (1984)	He	0.25
	Xe	0.65
	Air	0.61
Garnier & Begej (1979)	He	$0.425 - 2.3 \times 10^{-4}T$, T in K
	Xe	$0.749 - 2.5 \times 10^{-4}T$
	Ar	interpolation based on the atomic weight of the gas
Rapier et al. (1963)	Air	0.83
	H_2	0.26
	He	0.38
	Ar	0.85
Chandola & Loyalka (1982)	He	0.3, 0.07

CLEAN SURFACE TAC

Perhaps the most well known theory for clean surface TAC is the one by Boule(1914). He considered the exchange of translational kinetic energy between two hard sphere molecules and derived the expression:

$$\alpha = \frac{2\mu}{(1+\mu)^2} \tag{4}$$

where $\mu = \frac{M_g}{M_s}$
and M_g = molecular weight of gas
M_s = molecular weight of solid

This expression has the maximum value of $\frac{1}{2}$ when $\mu = 1$, and as μ becomes either smaller or larger α becomes smaller. Not surprisingly, the Boule formula is symmetrical about $\mu = 1$, *i.e.* $\alpha(\mu) = \alpha(\frac{1}{\mu})$.

When multiple-collision effects are considered, a more accurate expression (Goodman, 1967) may be derived:

$$\alpha = \frac{2.4\mu}{(1+\mu)^2} \tag{5}$$

This expression is later incorporated into a new correlation to account for the asymptotic behavior of TAC as the solid temperature increases. Accordingly, we shall use the notation α_∞ to denote this modified Boule formula:

$$\alpha_\infty(\mu) = \frac{2.4\mu}{(1+\mu)^2} \tag{6}$$

This expression is also used as an asymptotic function in the clean surface TAC model of Goodman and Wachman(1967). Their model is in good agreement with experimental data for the temperature range $0 < T < 500$ K.

The predicted values of α_∞ are compared with experimental data of DePoorter and Searcy(1963) in Table 2. The agreement is shown to be quite good. It is remarkable that the theory, which was developed for monatomic gases, also accurately predicts values of TAC for N_2 and CO_2.

Typical values of low temperature TAC data on clean tungsten surfaces is shown in Table 3. Also shown in the table are the values of α_∞.

The gas-temperature dependence of TAC on clean-tungsten surface is summarized in the review work by Goodman(1980). The TAC values of *Xe*, *Kr* and *Ar* decrease with gas temperature for T_g below about 300 K, and for T_g above 300 K show the trend of approaching the values predicted by the modified Boule formula (Eq. 5). For lighter gases, *He* and *Ne*, the minimum values of TAC are found at $T_g \simeq 100$ K as 0.01 and 0.05, respectively, and above this T_g the TAC values increase gradually with T_g, again, seemingly approaching the predicted values of the Boule formula.

ENGINEERING SURFACE TAC

Definition of Engineering Surfaces

Unless the surface of a solid is created in a vacuum or care is taken to remove adsorbed materials, most surfaces would be covered by layers of adsorption. For those surfaces that are exposed to ordinary air, the adsorption layers would consist of O_2, H_2O, CO_2 and perhaps other unknown gases. In addition to these, there would likely be oxide layers.

Table 2. Comparison of α_∞ with experimental data (DePoorter and Searcy, 1963)

Gas	$T_s(K)$	$\alpha_{exp}{}^*$	α_∞	% diff.
Ne	2120	0.237	0.214	-9.7
Ar	2335	0.332	0.352	5.9
N_2	2511	0.282	0.275	-2.4
CO_2	2120	0.365	0.374	2.4

* α_{exp} was measured on tungsten surface

Table 3. Low temperature TAC data on clean surface (Kouptisidis and Menzel, 1970)

Gas	$\alpha_{exp}{}^*$	α_∞
He	0.0167	0.050
Ne	0.0420	0.214
Ar	0.27	0.352
Kr	0.41	0.516
Xe	0.67	0.583

* tungsten surface, $T_s = 298$ K

There are two principal means (Mykura, 1966) of removing adsorbed material:

a) heating in a vacuum to a high temperature, typically above 1000–2000 K,

b) exposing the surface to an electric discharge in an inert gas environment.

Even then, there is the difficulty of maintaining the surface impurity-free. Therefore it is reasonable to assume that most engineering surfaces are covered with adsorption layers.

Effect of Adsorption on TAC

Some direct evidence concerning the effect of adsorption on TAC is shown in Table 4. It is seen that, depending upon the condition of the initial surface, adsorption can lead to an increase of TAC by as much as 5 times. In fact, if we consider the reliable clean surface TAC data of Table 3 for *He* and compare it with the TAC of adsorbed surfaces in Table 4, the ratio $\frac{\alpha_{adsorbed}}{\alpha_{He}}$ can be as large as 20–30.

Effects on TAC of different types of adsorbate gases have been studied by Wachman(1957) and Thomas(1967). Of the studied adsorbate gases, H_2, D_2, O_2, N_2, CO_2, CH_4, C_2H_6, and C_2H_4, O_2 was found to have the most pronounced effect by increasing the clean surface TAC of *He* about tenfold.

Effect of Surface Roughness on TAC

Perhaps the first mentioned and most quoted work on the effect of surface roughness is that by Roberts(1930), who recommended the relationship:

$$\alpha = 1 - (1 - \alpha_0)^n \tag{7}$$

where α_0 = TAC of ideal smooth surface
n = number of collisions a gas molecule experiences before rebounding from the surface

Table 4. Effect of adsorption on TAC

Gas-Solid	$T_s(K)$	α_{clean}	$\alpha_{adsorbed}$	Author(s)
$He - W$	room temp.	0.17*	0.53	Michels(1932)
$Ar - W$	room temp.	0.82*	1.00	Michels(1932)
$He - Pt$	308	0.18*	0.43	Thomas & Golike(1954)
$He - Ni$	273	0.069	0.36	Raines(1939)
$He - Pt$	273	0.071	0.17	Rolf(1944)

* These values are much higher than other reliable data (such as those shown in Table 3), and perhaps the surfaces are slightly gas covered.

Thomas and Lord(1974) made TAC measurements for various inert gases on polished (r.m.s. roughness of 0.1 μm) and rough (r.m.s. roughness estimated at $\sim 1 \mu m$) steel spheres. Table 5 shows the comparison of TAC values for the two different surfaces. In general the measured values appear quite high. They claim, however, that the ratio $\frac{\alpha_{rough}}{\alpha_{polished}}$ should be correct. It is seen from the table that the surface roughness effect appears to be significant only for light gases. Wiedmann and Trumpler(1946) conducted experiments to determine the TAC of air on bronze, cast iron and aluminum, each of which were prepared with three different finishing processes: polishing, machining and etching. They concluded that all measured values of TAC lie between 0.87 and 0.97, but the effect of different technical surfaces was not observed.

Terekhov and Frolova(1971) developed an experimental correlation using the same functional form of Eq. 7:

$$\alpha = 1 - (1 - \alpha_0)^{1 + D \tan\theta} \tag{8}$$

where $\tan\theta$ = mean asperity slope
D = correlation coefficient

Several values of the correlation coefficient D were obtained for He, Ar, CO_2 and Air (See Table 6). If we use this correlation and estimate the ratio $\frac{\alpha}{\alpha_0}$ for He with $\alpha_0 = 0.35$ and $\tan\theta = 0.15$, which are the typical values used in Hegazy's(1985) thesis work, we obtain $\frac{\alpha}{\alpha_0} = 1.16$. On the other hand, for N_2 the correlation predicts $\frac{\alpha}{\alpha_0} = 1.03$.

It seems that for light gases the surface roughness effect on TAC is in the vicinity of $10 \sim 20\%$. For heavier gases, however, the effect appears to be less significant.

Table 5. Surface roughness effect of TAC (Thomas and Lord, 1974)

Gas	$\alpha_{polished}$	α_{rough}	$\frac{\alpha_{rough}}{\alpha_{polished}}$
He	0.425	0.553	1.30
Ne	0.766	0.865	1.13
Ar	1.102	1.161	1.05
Kr	1.134	1.175	1.04
Xe	1.395	1.395	1.00

Table 6. Values of correlation coefficient D $\alpha = 1 - (1 - \alpha_0)^{1 + D \tan\theta}$ (Terekhov and Frolova, 1971)

Gas	D
He	1.35
Ar	1.36
CO_2	0.9
Air	0.905

DEVELOPMENT OF CORREALTION FOR ENGINEERING-SURFACE TAC

Selection of Parameters and Functional Form

The parameters which may possibly influence the TAC for engineering surfaces can be identified as:

$$\alpha = f(M_g, M_s, M_a, F, T_g, T_s) \tag{9}$$

where M_g = molecular weight of the gas
M_s = molecular weight of the solid
M_a = effective molecular weight of the adsorption layer
F = fraction of the surface covered by adsorption layer
T_g = temperature of the gas
T_s = temperature of the solid

We first assume that the TAC is the weighted sum of two quantities α_a and α_c, each representing the TAC for fully adsorbed and clean surfaces, respectively:

$$\alpha = F\alpha_a + (1 - F)\alpha_c \tag{10}$$

Then, the obvious choice for α_c appears to be the modified Boule formula (Eq. 6):

$$\alpha_c = \alpha_\infty = \frac{2.4\mu}{(1 + \mu)^2} \tag{11}$$

Another assumption is now made that when the surface is fully adsorbed, it is the adsorbate layers that the gas molecules interact with, and thus the type of the substrate solid, under the fully adsorbed condition, has no influence on TAC. Furthermore, we assume that the modified Boule formula (Eq. 6), when M_s is replaced by M_a, provides qualitatively good predictions of TAC. Thus, the following functional form is considered for α_a:

$$\alpha_a = \frac{C_2 M_g}{(C_1 + M_g)^2} \tag{12}$$

where C_1 and C_2 are correlation constants to be determined.

It was found, however, that the following functional form provides a significantly better fit to the experimental data:

$$\alpha_a = \frac{C_2 M_g}{C_1 + M_g} \tag{13}$$

The fractional coverage, F, of the adsorption layer depends upon the surface temperature, T_s. However, the extent to which F depends on T_s is not obvious. When the temperature of the solid is near room temperature, the surface would probably be covered by several layers of adsorbate gases. As the surface temperature increases, the adsorption layers would be removed at some rate. The rate of increase of the fractional coverage, F, would be slow initially, because of the multilayer effect, and would become more rapid as T_s further increases. Therefore, an exponential form is considered for F:

$$F = exp\left[C_0\left(\frac{T_s - T_0}{T_0}\right)\right] \tag{14}$$

where T_0 is some reference temperature and C_0 is another correlation coefficient.

Now, we have the functional form of TAC:

$$\alpha = F\left[\frac{C_2 M_g}{C_1 + M_g}\right] + (1 - F)\left[\frac{2.4\mu}{(1+\mu)^2}\right] \tag{15}$$

where F is as defined in Eq. 14 and C_0, C_1, C_2 are the correlation coefficients to be determined.

Selection of Data for Correlation

Table 7 shows the sources of data acquired for correlation. It was decided to use only the data for monatomic gases, mainly because of the uncertainties associated with the effects on TAC of additional forms of energy transfer, namely the rotational and the vibrational. The effects on TAC of these additional forms of energy transfer for diatomic/polyatomic gases are taken into account, later, by introducing a 'monatomic equivalent molecular weight', which, then, allows the use of the monatomic-gas correlation to predict the TAC value of diatomic/polyatomic gases.

The data set for the correlation consists of five different inert gases on six different solids for the temperature range of $273 \leq T_s \leq 1250$ K. In selecting the data, care was taken to choose only those data for which no special effort was made to clean the surface of the solid. These are shown in Fig. 1.

Table 7. Sources of data used in the correlation

Author	Surface	Gas	$T_s(K)$
Thomas & Brown (1950)	Pt	He, Ne, Ar Kr	312–645
Amdur & Guildner (1957)	Ni	He, Ne, Ar Kr, Xe	282–373
Raines(1939)	Ni	He	273–369
Braun(1976)	stainless steel	He, Ar	273–573
Teagan & Springer (1968)	Al	Ar	296
Ullman et al.(1974)	UO_2 stainless steel	He, Xe	662–1250
Thomas & Loyalka (1982a)	$Zr-2$	He, Ar, Xe	300
Thomas & Loyalka (1982b)	UO_2	He, Ne, Ar Xe	308

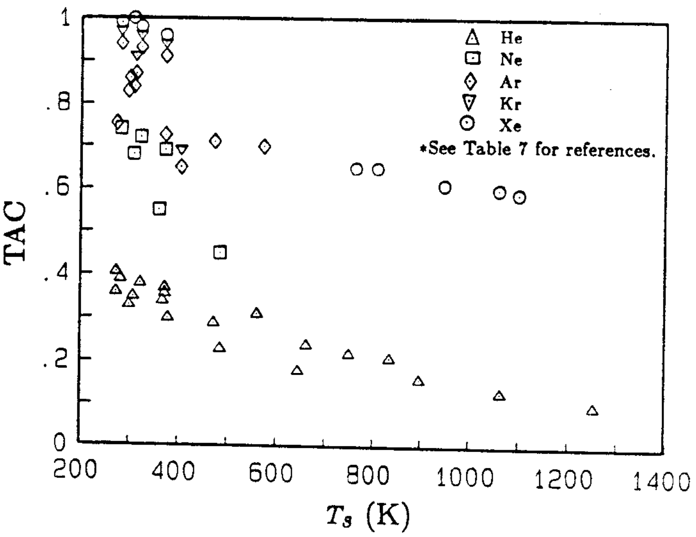

Figure 1. Selected data (monatomic gases) for correlation.

Correlation of α_a

For fully-adsorbed conditions, F, by its definition, is 1, and Eq. 15 reduces to the following:

$$\alpha_a = \alpha(T = T_0) = \frac{C_2 M_g}{C_1 + M_g} \tag{16}$$

Taking the inversion on both sides:

$$\frac{1}{\alpha_a} = \frac{1}{\alpha(T = T_0)} = \left(\frac{C_1}{C_2}\right)\frac{1}{M_g} + \left(\frac{1}{C_2}\right) \tag{17}$$

If the functional form of α_a chosen is appropriate, then the dependence of $\frac{1}{\alpha_a}$ on $\frac{1}{M_g}$ should be linear. Figure 2 shows the dependence of $\frac{1}{\alpha}$ on $\frac{1}{M_g}$ for the data with T_s between 273 and 320 K. We see from the figure, that the relationship is nearly linear.

A graphical fit of a straight line to the data in Fig. 2 produces the values of $C_1 = 6.8$ and $C_2 = 1$. The value for C_2 is intentionally set to 1, so that the values of α_a for all M_g never exceed 1. With these constants Eq. 16 becomes:

$$\alpha_a = \frac{M_g}{6.9 + M_g} \tag{18}$$

Also, it seems reasonable to set the reference temperature T_0 to 273 K, and to restrict the valid range of the correlation to $T_s \geq 273$ K.

Correlation of F

Having correlated α_a, we may, now, rewrite Eq. 10 for F, whose functional form is defined in Eq. 14:

$$F = exp\left[C_0\left(\frac{T_s - T_0}{T_0}\right)\right] = \frac{\alpha - \alpha_\infty}{\alpha_a - \alpha_\infty} \tag{19}$$

where $T_0 = 273$ K.

Equation 19 can be linearized with respect to T_s by taking the natural logarithm on both sides, and when the sides are exchanged:

$$\ln\left[\frac{\alpha - \alpha_\infty}{\alpha_a - \alpha_\infty}\right] = C_0\left(\frac{T_s}{T_0} - 1\right) \qquad (20)$$

The values of $\dfrac{\alpha - \alpha_\infty}{\alpha_a - \alpha_\infty}$ for the data in Table 7 are shown in Fig. 3 on a logarithmic scale, and it is observed that the assumption of a linear relationship in Eq. 20 appears reasonable.

Again, a graphical fit of a straight line to the data in Fig. 3, with the constraint of $\dfrac{\alpha - \alpha_\infty}{\alpha_a - \alpha_\infty} = 1$ at $T_s = T_0$, results in the value for C_0 of −0.57.

Finally, we obtain the full correlation for α:

$$\alpha = exp\left[C_0\left(\frac{T_s - T_0}{T_0}\right)\right]\left(\frac{M_g}{C_1 + M_g}\right) + \left\{1 - exp\left[C_0\left(\frac{T_s - T_0}{T_0}\right)\right]\right\}\left\{\frac{2.4\mu}{(1+\mu)^2}\right\} \qquad (21)$$

where $C_0 = -0.57$, $C_1 = 6.8$, and $T_0 = 273$ K.

Modification for Diatomic and Polyatomic Gases

The exchange of energy between solid surfaces and diatomic or polyatomic gases involves the rotational and vibrational energies, in addition to the translational energy. Thus, the TAC correlations based on monatomic gases may require adjustments to take into account the effects of the additional forms of the energy exchange.

It is difficult to base such adjustments on theoretical understanding of the individual form of the energy exchange. In this work, instead, we shall deal with the global value of TAC, and assume that the global effect on TAC of the individual form of the energy exchange is related, in a simple form, to the molecular weight of the diatomic and polyatomic gases.

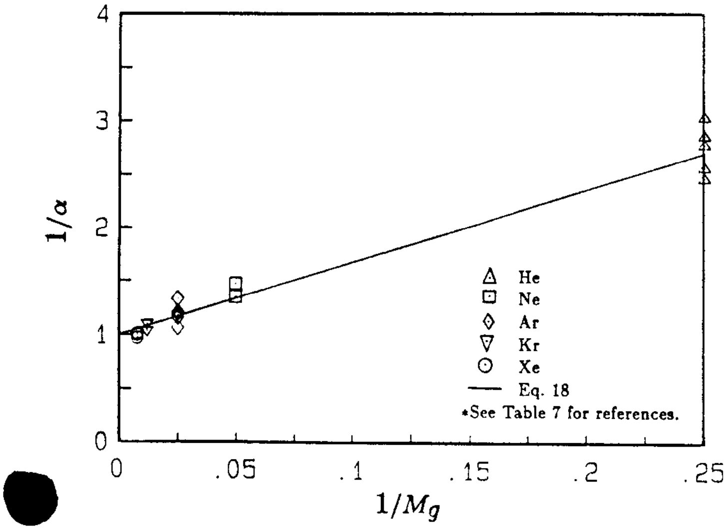

Figure 2. Dependence of $\frac{1}{\alpha_a}$ upon $\frac{1}{M_g}$ (monatomic gases).

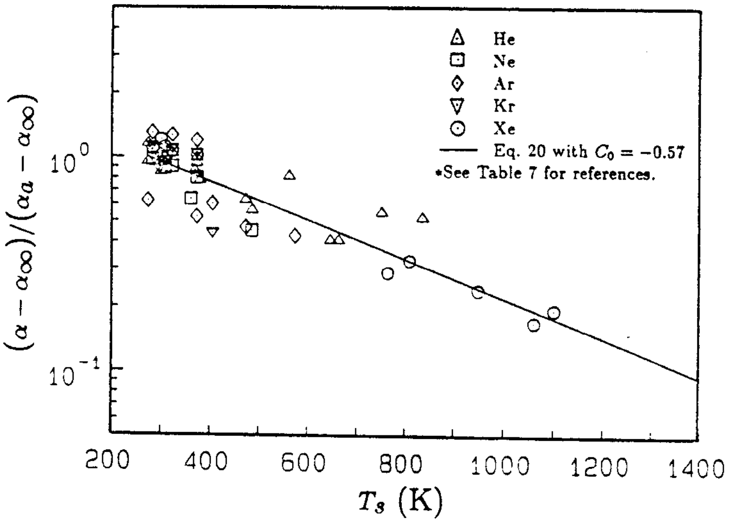

Figure 3. Dependence of $\frac{\alpha - \alpha_\infty}{\alpha_a - \alpha_\infty}$ upon T_s (monatomic gases).

First, we define $M_g{}^*$ to be the monatomic equivalent molecular weight of diatomic/polyatomic gas, such that the TAC of the gas is the same as that of a monatomic gas with the molecular weight $M_g = M_g{}^*$. Furthermore, a simple relationship is assumed between M_g and $M_g{}^*$:

$$M_g{}^* = GM_g \qquad (22)$$

The constant, G, can be determined by comparing the values of C_1 in Eq. 17 for monatomic gases and for diatomic/polyatomic gases, provided that the value of C_2 can be set to 1 for diatomic/polyatomic gases.

Tables 8 and 9 show the values of TAC collected from various authors for diatomic and polyatomic gases, respectively. These values are for 14 different gases on 5 different types of solids over the solid temperature range of 273 to 383 K.

Figure 4 shows the relationship between $\frac{1}{\alpha}$ and $\frac{1}{M_g}$ of diatomic/polyatomic gases with $T_s < 320$ K. A graphical fit of a linear line to the data shown in the figure results in the values of C_1 and C_2 of 4.9 and 1, respectively. Following the comparison

Table 8. TAC measurements for diatomic gases

Author	Surface	Gas	$T_s(K)$
Amdur & Guildner (1957)	W, Ni, Pt	H_2, D_2, N_2, O_2	283, 298
von Ubisch(1951)	W, Pt	H_2, D_2, N_2, O_2	373
Dickens(1934)	Pt	H_2, N_2, CO, O_2	291, 297
Chavken(1955)	Pt	H_2, D_2, N_2 CO, O_2	290

Table 9. TAC measurements for polyatomic gases

Author	Surface	Gas	$T_s(K)$
Grau(1949)	Pt	CS_2	273–359
Schäfer & Gerstäcker(1956)	Pt, Ag	N_2O	293–383
Thomas & Golike(1954)	Pt	CO_2	314–353
Schäfer(1952)	Pt, Cu	C_2H_6	293–370
von Ubisch(1951)	Pt	$H_2S, SO_2, C_2H_4,$ C_2H_6, C_3H_2	373
Schäfer & Klingenberg(1954)	Pt	CO_2	293–373

of C_1 values for monatomic and diatomic/polyatomic gases, the constant G is found to be $G = \frac{C_{1monatomic}}{C_{1diatomic/polyatomic}} = 1.4$.

Finally, the general form of the TAC correlation, applicable to all monatomic and diatomic/polyatomic gases, is:

$$\alpha = exp\left[C_0(\frac{T_s - T_0}{T_0})\right]\left(\frac{M_g^*}{C_1 + M_g^*}\right)$$

$$+\left\{1 - exp\left[C_0\left(\frac{T_s - T_0}{T_0}\right)\right]\right\}\left\{\frac{2.4\mu}{(1+\mu)^2}\right\} \qquad (23)$$

where M_g* = M_g for monatomic gases
= 1.4 M_g for diatomic/polyatomic gases
C_0 = −0.57, dimensionless
C_1 = 6.8, units of M_g (g/mole)
μ = $\frac{M_g}{M_s}$
T_0 = 273 K

COMPARISON OF CORRELATION WITH EXPERIMENTAL DATA

Figures 5 through 9 show the comparison between the predicted and experimental values of TAC for the 5 monatomic gases, *He*, *Ne*, *Ar*, *Kr*, and *Xe*. In general, the predicted values are in good agreement with experimental data.

Figure 9 includes two sets of *Xe* data on stainless steel by Ullman et al.(1974), one of which was not used in the new correlation; this is the set with lower TAC values in the T_s range of 700 – 1100 K. This set of data were measured with an incident beam angle much smaller than 45° and, thus, should not be considered as representative TAC for the corresponding gas-solid combination. The other set of *Xe* data (the higher values) were measured with the incident angle of 45°, and these are in excellent agreement with the predicted values of the new correlation.

Both sets of *Xe* data and their *He* data were also correlated by Lanning and Hann(1975), and their correlation is compared in Figs. 5 and 9.

The TAC values of diatomic/polyatomic gases predicted by the correlation (Eq. 23) are compared with experimental data (Tables 8 and 9) in Fig. 10. In general, the agreement between the experimental and the predicted values is within 25 percent.

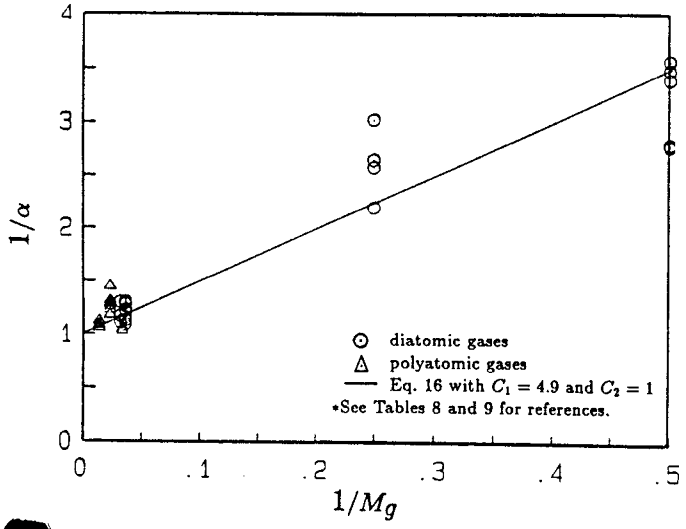

Figure 4. Dependence of $\frac{1}{\alpha_a}$ upon $\frac{1}{M_g}$ (diatomic/polyatomic gases).

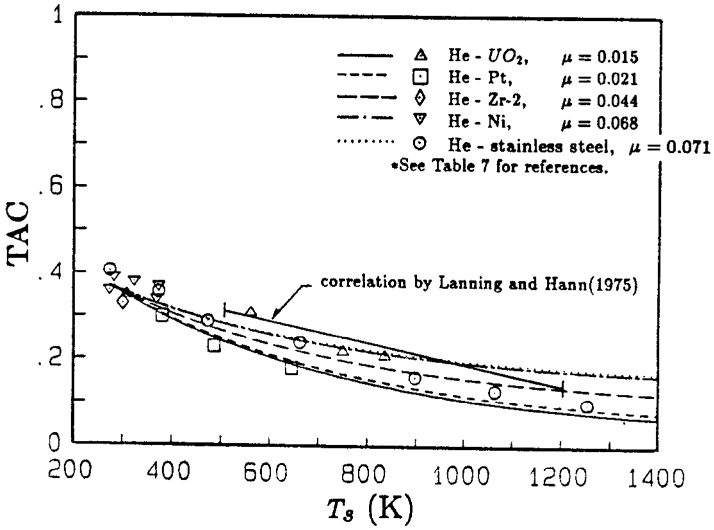

Figure 5. Comparison between predicted and experimental values of TAC for Helium.

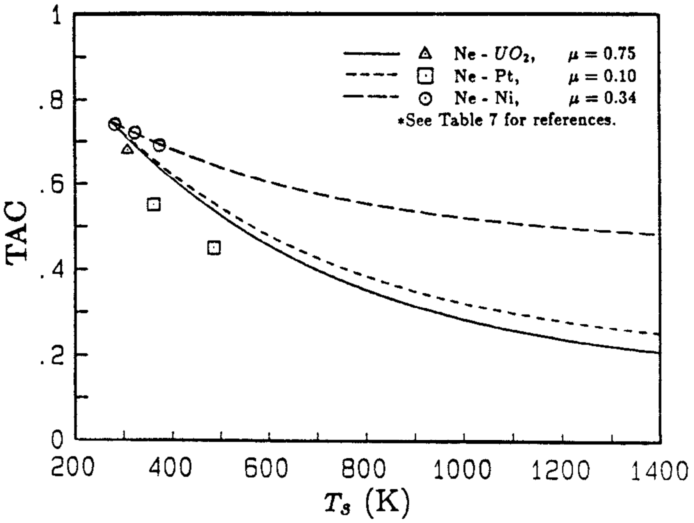

Figure 6. Comparison between predicted and experimental values of TAC for Neon.

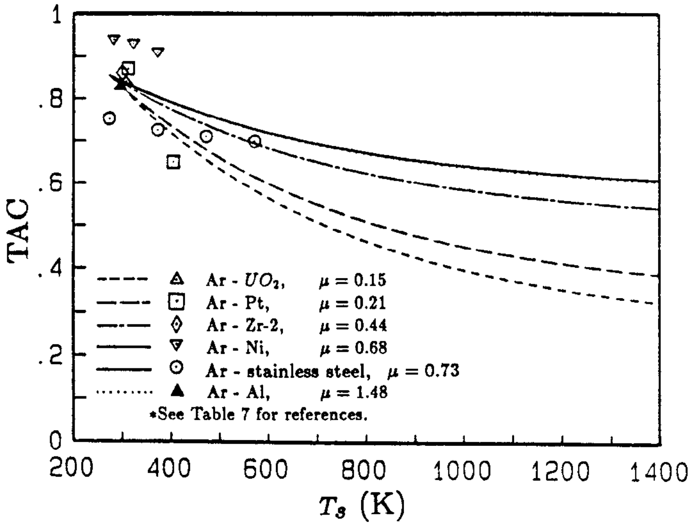

Figure 7. Comparison between predicted and experimental values of TAC for Argon.

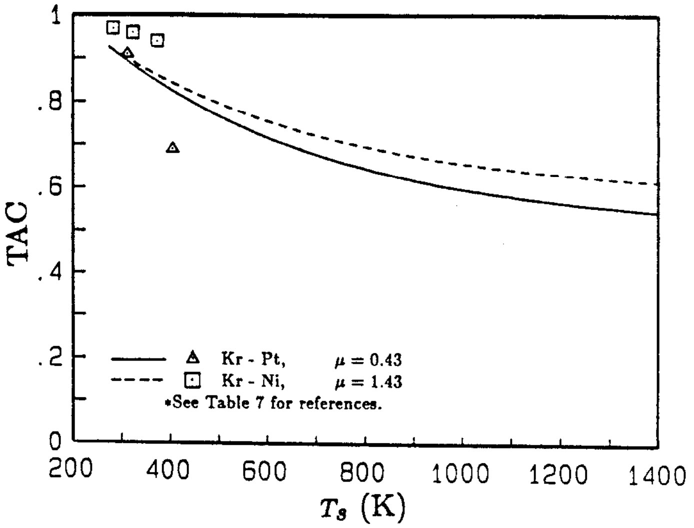

Figure 8. Comparison between predicted and experimental values of TAC for Krypton.

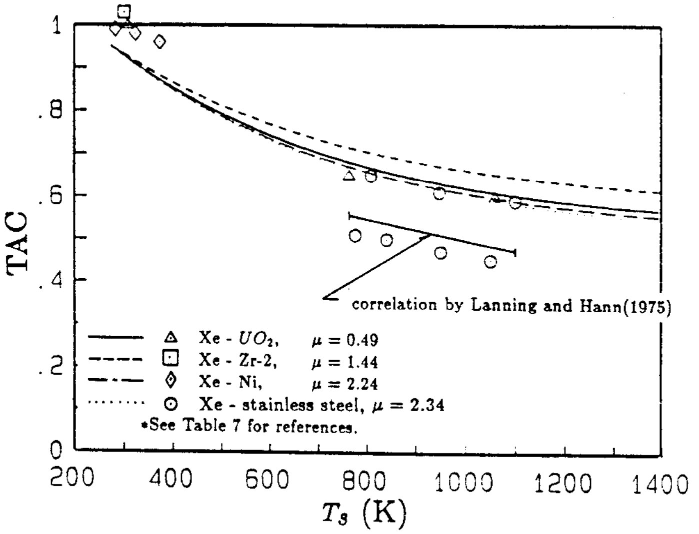

Figure 9. Comparison between predicted and experimental values of TAC for Xenon.

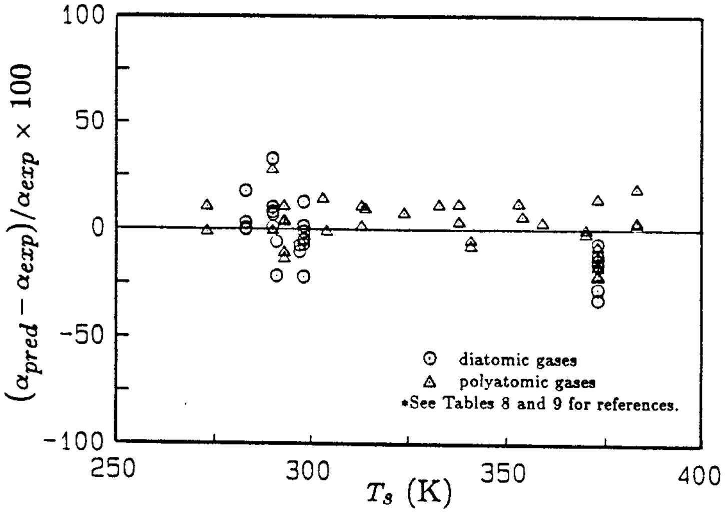

Figure 10. Percent difference between predicted and experimental values of TAC for diatomic/polyatomic gases.

DISCUSSION

The correlation developed, here, is the result of an attempt to bring together, from the thermal engineering designer's point of view, the current understanding of TAC, which is a lumped parameter to represent the complicated process of energy exchange at a solid/gas interface in a rarefied-gas environment.

Let alone the understanding of the effects of various parameters which control the condition of the phenomenon, we are far from comprehending the process itself of this energy exchange at a molecular level. Yet, the importance of the role of TAC in many areas involving heat transfer, such as the contact of solids, chemical reactors, and aerospace flights, requires the means to estimate this parameter and some assessment of uncertainties associated with such means.

The new correlation, which is intended for use with engineering surfaces, identifies as main parameters the surface temperature and the molecular weight of the gas and the solid. The correlation neglects the possible effects on TAC of other parameters, such as the gas temperature, the difference in the temperatures of the gas and the solid, and the gas pressure. The authors believe the effects of these neglected parameters are secondary, and have attempted, during the course of the development of the correlation, to provide justifications.

Finally, the authors suggest this correlation should be used in conjunction with references made to actual experimental data corresponding to the particular gas-solid combination and similar surface conditions. For such purposes, the reader's attention is called to the excellent and comprehensive collection of experimental data by Saxena and Joshi(1981).

SUMMARY

Effects on TAC of adsorption and surface roughness were briefly discussed. TAC depends greatly upon the adsorption condition of the surface, and its value for an engineering surface can be 10 or 20 times greater than that for clean surface. The surface-roughness effect is less significant and is of concern only for light gases, in which case the effect is estimated to be in the order of 10–20 percent.

A correlation for engineering-surface TAC was developed using the experimental data for monatomic gases by various authors on several types of adsorbed surfaces. Embedded in the correlation is a well-known clean surface TAC formula, which has been shown to agree well with the experimental data at very high surface temperature. The TAC value for diatomic/polyatomic gases can also be estimated by first evaluating their monatomic equivalent molecular weight and applying this directly with the developed correlation. In general, the agreement between the predicted and experimental values of TAC for both monatomic and diatomic/polyatomic gases is within 25 percent.

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REFERENCES

Amdur, I., and Guildner, L.A., 1957, "Thermal Accommodation Coefficients on Gas-covered Tungsten, Nickel and Platinum," J. Amer. Chem. Soc., Vol. 79, pp. 311–315.

Boule, B., 1914, "Theoretische Behandlung der Erscheinungen in Verdünnter Gasen," Ann. der Physik, Vol. 44, No. 1, pp. 145–176.

Braun, D., 1976, "Wärmetransport in Grasen bei grossen Temperaturdifferenze und beliebigen Knudsenzahlen," Dissertation, RWTH, Aachen.

Chandola, V.K., and Loyalka, S.K., 1982, "Gap Conductance and Temperature Transients in Modified Pulse Design Experiments," Nuclear Technology, Vol. 56, pp. 434–446.

Chavken, L.P., 1955, "The Measurement of the Pressure of Several Gases with a Thermovapor Manometer," J. Techn. Physics (S.S.S.R.), Vol. 25, pp. 726–732.

DePoorter, G.L., and Searcy, A.W., 1963, "Energy Exchange Between a Hot Tungsten Surface and Cold Gases," J. Chem. Phys., Vol. 39, No. 4, pp. 925–930.

Dharmadurai, G., 1984, "Analysis of Photocoustically Investigated Gaseous Heat Transfer Between Solid Surfaces," Phys. Stat. Sol. A, Vol. 83, pp. K27–K30.

Dickens, B.G., 1934, "The Effect of Accommodation on Heat Conduction Through Gases," Proc. Roy. Soc (London), Vol. A143, pp. 517–540.

Garnier, J.E., and Begej, S., 1979, "Ex-Reactor Determination of Thermal Gap and Contact Conductance Between Uranium Dioxide: Zircaloy-4 Interfaces," U.S. Nuclear Regulatory Commission Report.

Goodman, F.O., 1967, "Three-Dimensional Hard Spheres Theory of Scattering of Gas Atoms from a solid Surface I. Limit of Large Incident Speed," Surf. Sci., Vol. 7, pp. 391–421.

Goodman, F.O., 1980, "Thermal Accommodation Coefficients," J. Phys. Chem., Vol 84, pp. 1431–1445.

Goodman, F.O., and Wachman, H.Y., 1967, "Formula for Thermal Accommodation Coefficients," J. Chem. Phys., Vol. 46, No. 6, pp. 2376–2386.

Goodman, F.O., and Wachman, H.Y., 1976, "Dynamics of Gas-Surface Scattering," Academic Press.

Grau, G.G., 1949, "Die Akkommodation und Adsorption von Gasen an festen Oberflächen," Z. Elektrochem. angew. physik Chem., Vol. 53.

Hartnett, J.P., 1961, "A Survey of Thermal Accommodation Coefficients," Rarefied Gas Dynamics, L. Talbot, ed., Academic Press, pp. 1–28.

Hegazy, A.A., 1985, "Thermal Joint Conductance of Conforming Rough Surfaces:Effect of Surface Micro-Hardness Variation," Ph.D Thesis, University of Waterloo, Waterloo, Ontario.

Kaminski, M., 1965, "Atomic and Ionic Impact Phenomena on Metal Surfaces," Academic Press.

Knudsen, M., 1911, "Molecular Heat Conductivity of Gases and the Coefficient of Accommodation," Ann. der Physik, Vol. 34, pp. 593–656.

Kouptsidis, J., and Menzel, D., 1970, Ber. der Bunsenges. Physik Chem., Vol. 74, pp. 512–520.