

Analyzing gas-surface interactions using the reduced force coefficients

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The reduced force coefficients are introduced as a new set of parameters that can be used to analyze the momentum transferred to surfaces by incident molecules in rarefied flow regimes. These coefficients are well-defined for all angles of incidence, thereby eliminating the singularity problems associated with the momentum accommodation coefficients. The reduced force coefficients can be obtained from measurements of the forces exerted on surfaces by molecular beams, and can be used to obtain the flux-weighted average velocity of the molecules scattered from surfaces. Also, a method is developed that can be used to approximate the flux-weighted average translational energy of the scattered molecules and the energy accommodation coefficient for many gas-surface interactions. Measurements of the forces exerted on SiO₂-coated Kapton and Z-93-coated Al by molecular beams of N₂ and H₂ are used to demonstrate the singularity problems associated with the momentum accommodation coefficients. The same force measurements are then used to calculate the reduced force coefficients and several macroscopic average quantities of the scattered molecules.

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I. INTRODUCTION

When a gas collides with a surface, the incident molecules experience forces that depend upon the microscopic gas-surface interaction potential. Since these forces change the average momentum of the incident molecules, a nonzero net force must be exerted on the surface by the gas. The collisions are in general inelastic and result in a transfer of energy between the incident gas and the surface that usually leads to a change in surface temperature [1–4]. These interactions can be further complicated by changes in energy associated with the internal degrees of freedom of the gas [1–5] and by adsorption or reactions of the gas with the surface [6]. Traditionally, microscopic information about gas-surface interactions has been obtained from measurements of velocity, angular, and internal state distribution functions of the incident and scattered molecules [1–12]. Much information about gas-surface interactions can be obtained from the difference between these functions before and after the surface scattering event.

In this paper a new formalism is developed that can be used to study gas-surface interactions by analyzing the macroscopic average force exerted on a surface by an incident gas. Because forces exerted on surfaces by incident molecules are coupled to the gas-surface interaction potentials, microscopic information of gas-surface interactions can be obtained from measurements of these forces. Also, measurements of the forces can be used to obtain the flux-weighted average [13] (hereafter referred to as average) velocity and average energy of the scattered molecules. Determining macroscopic average quantities from microscopic measurements of the velocity and internal state distribution functions of the scattered molecules usually requires many assumptions that limit the accuracy of the results [14,15]. However, torsion balances can be used to measure the forces exerted on surfaces by molecular beams with uncertainties of less than $\pm 1\%$ [16]. Due to the versatility of molecular beam sources, these quantities can in principle be measured as a function of

incident energy, direction, internal state, and angular momentum orientation. Thus, the method described in this paper can be used to obtain information about gas-surface interactions that usually has not been obtained from more microscopic measurements.

The momentum accommodation coefficients have traditionally been used to describe the macroscopic average transfer of momentum to a surface by an incident gas [17,18]. However, singularities render these coefficients nearly unusable for many gas-surface interactions [19,20]. The new formalism developed in this paper is based upon two parameters called the reduced force coefficients. These coefficients are well-defined and can be used to completely analyze the macroscopic average transfer of momentum to a surface by an incident gas. Properties of the reduced force coefficients and the singularity problems associated with the normal momentum accommodation coefficient are illustrated using measurements of actual forces exerted on surfaces by molecular beams.

II. THE MOMENTUM ACCOMMODATION COEFFICIENTS

Traditionally the normal and tangential momentum accommodation coefficients have been used to study momentum transferred to surfaces by incident gases in rarefied flow regimes. Definitions of the coefficients were arrived at by considering the limiting cases of specular reflection and diffuse scattering with complete thermal accommodation [17,18]. It was thought that the coefficients would range between zero for pure specular reflection and one for diffuse scattering with complete thermal accommodation. However, in this section it will be shown that both momentum accommodation coefficients actually diverge for most gas-surface interactions.

The tangential σ and normal σ' momentum accommodation coefficients are defined by the equations [17,18]

$$\sigma = \frac{\bar{p}_{it} - \bar{p}_{st}}{\bar{p}_{it}}, \quad (1)$$

$$\sigma' = \frac{\bar{p}_{in} - \bar{p}_{sn}}{\bar{p}_{in} - \bar{p}_d}, \quad (2)$$

where \bar{p} is the magnitude of the average momentum, the subscripts i and s , respectively, refer to the incident and scattered molecules, the subscripts t and n , respectively, are the tangential and normal components, and the subscript d represents diffuse scattering from the surface with complete thermal accommodation. For a molecular beam incident upon the surface, the coefficients can be expressed as

$$\sigma = \frac{\bar{v}_i \sin \theta_i - \bar{v}_s \sin \theta_s}{\bar{v}_i \sin \theta_i}, \quad (3)$$

$$\sigma' = \frac{\bar{v}_i \cos \theta_i - \bar{v}_s \cos \theta_s}{\bar{v}_i \cos \theta_i - \sqrt{\pi k T / 2m}}, \quad (4)$$

where \bar{v} is the magnitude of the average velocity, θ is the angle between the average velocity and the surface normal, m is the mass of individual molecules in the molecular beam, k is Boltzmann's constant, and T is the temperature of the scattering surface. The radical term in Eq. (4),

$$\sqrt{\pi k T / 2m}, \quad (5)$$

is the magnitude of the average velocity of the scattered molecules assuming diffuse scattering from the surface with complete thermal accommodation.

For applications where molecules scatter from the surface with azimuthal symmetry when the angle of incidence θ_i is equal to zero, the tangential momentum accommodation coefficient has a removable singularity since

$$\lim_{\theta_i \rightarrow 0} \sigma \theta_i = 0, \quad (6)$$

and no further attention is required. However, if the scattering angle θ_s is not equal to zero for incident gas flows normal to the scattering surface, the tangential coefficient would diverge.

Problems with the normal momentum accommodation coefficient, however, are much more severe. For many gas-surface interactions $\theta_i > \theta_s$. Thus, the possibility exists that

$$\sqrt{\pi k T / 2m} < \bar{v}_i \cos \theta_i \leq \bar{v}_s \cos \theta_s. \quad (7)$$

If the condition in Eq. (7) is met, the normal coefficient can be zero or even attain negative values. Thus, for many applications, the value of the normal accommodation coefficient does not provide an accurate measure of accommodation.

A more serious problem associated with the normal momentum accommodation coefficient is due to a singularity at the critical angle of incidence θ_c given by

$$\theta_c = \cos^{-1} \sqrt{\frac{\pi k T}{2m\bar{v}_i^2}}. \quad (8)$$

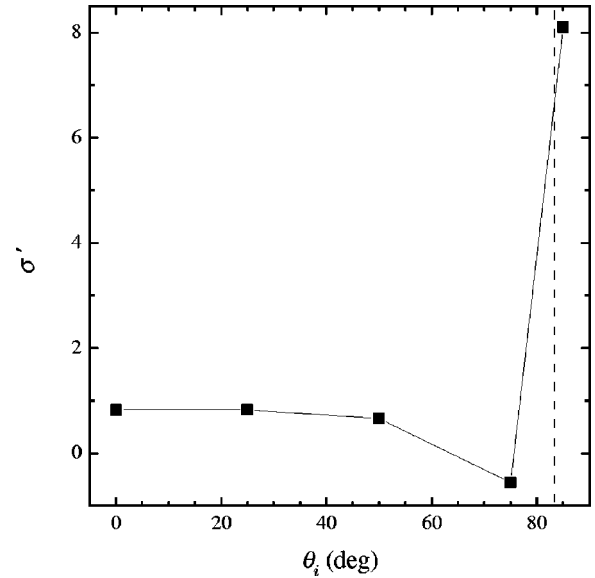


FIG. 1. The normal momentum accommodation coefficient for N_2 incident upon SiO_2 -coated Kapton with an average velocity of 3180 m/s. The dashed vertical line at 83° represents the position of the singularity in Eq. (4).

This singularity results in divergent behavior for essentially every application involving a directed gas flow. In addition, the singularity position is a function of the temperature of the scattering surface, the molecular mass, and the average velocity of the incident molecules. For applications where θ_c is close to 90° and the gas impinges upon the surface at angles of incidence near the surface normal, the effects of the singularity can be insignificant. However, even if θ_c is close to 90° , the singularity can cause dramatic effects when the gas impinges upon the surface at angles of incidence greater than 50° [21].

Actual measurements are used to demonstrate the problems associated with the normal momentum accommodation coefficient for a molecular beam of N_2 with an average velocity of 3180 m/s incident upon a surface of SiO_2 -coated Kapton [20]. The surface was at room temperature, and no special attention was taken to clean or prepare it in any way. The coefficient σ' was determined from measurements of the force exerted on the surface by the molecular beam using a torsion balance [21,16]. Measurements were made at angles of incidence of 0° , 25° , 50° , 75° , and 85° . The total uncertainty in the force measurements was estimated to be approximately $\pm 1\%$. The molecular beam was produced using a supersonic nozzle source that is described in detail elsewhere [16,22]. The measured values for σ' are shown in Fig. 1. As the angle of incidence increases beyond 50° , σ' becomes smaller until it becomes negative at approximately 65° . Between 65° and θ_c , the numerator in Eq. (4) is negative and the denominator is positive. For angles of incidence greater than θ_c , both numerator and denominator in Eq. (4) are negative, making the coefficient positive. The momentum accommodation coefficients were defined to analyze the momentum transferred to surfaces by incident molecules and to be a measure of the accommodation that takes place during a scattering process. The measurements shown in Fig. 1

clearly demonstrate that σ' cannot be used for either purpose when molecules are incident upon surfaces at angles of incidence near the singularity.

To overcome this problem Knuth [19] defined the normal momentum transfer coefficient α'_{NM} given by

$$\alpha'_{\text{NM}} = \frac{\bar{p}_{in} + \bar{p}_{sn}}{\bar{p}_{in}}. \quad (9)$$

For a molecular beam incident upon a surface α'_{NM} can be expressed as

$$\alpha'_{\text{NM}} = 1 + \frac{\bar{v}_s \cos \theta_s}{\bar{v}_i \cos \theta_i}. \quad (10)$$

The ratio \bar{v}_s/\bar{v}_i is finite and greater than zero for nearly all gas-surface interactions. However, the ratio $\cos \theta_s/\cos \theta_i$ diverges as the angle of incidence approaches 90° for essentially all gas-surface interactions. The only exception would be for specular scattering where

$$\lim_{\theta_i \rightarrow 90^\circ} \theta_s = 90^\circ. \quad (11)$$

This coefficient has the advantage that it removes the functional dependence of the singularity upon the surface temperature, the molecular mass, and the average velocity of the incident molecules. However, α'_{NM} diverges at large angles of incidence for essentially every realistic scattering process. To avoid the problems associated with singularities, a new formalism was developed based upon parameters that are well-defined for all angles of incidence.

III. THE REDUCED FORCE COEFFICIENTS

The new formalism is based upon two parameters called the reduced force coefficients [20]. The definitions of these coefficients can be motivated by a consideration of the force exerted on a surface by a molecular beam. The average net force \mathbf{F} exerted on a surface by a molecular beam is given by

$$\mathbf{F} = N_i \bar{\mathbf{p}}_i - N_s \bar{\mathbf{p}}_s, \quad (12)$$

where N represents molecules per unit time. For a typical case, $\bar{\mathbf{p}}_i$ and $\bar{\mathbf{p}}_s$ would most likely be on opposite sides of the surface normal. Also, for most applications

$$\bar{p}_{it} > \bar{p}_{st}. \quad (13)$$

Thus, the magnitude of tangential force component F_t would be given by

$$F_t = N_i \bar{p}_{it} - N_s \bar{p}_{st}, \quad (14)$$

and since the normal components of $\bar{\mathbf{p}}_i$ and $\bar{\mathbf{p}}_s$ are in opposite directions, the normal force component F_n would be given by

$$F_n = N_i \bar{p}_{in} + N_s \bar{p}_{sn}. \quad (15)$$

Differences between N_i and N_s can result by additional molecules outgassing from the surface and by incident gas mol-

ecules condensing upon or reacting with the surface. For all remaining equations it will be assumed that

$$N_i = N_s. \quad (16)$$

This assumption is applicable for nonreactive gases incident upon clean surfaces or whenever

$$\frac{N_i - N_s}{N_i} \approx 0. \quad (17)$$

Using Eqs. (14)–(16),

$$\frac{F_t}{N_i} = \bar{p}_{it} - \bar{p}_{st}, \quad (18)$$

$$\frac{F_n}{N_i} = \bar{p}_{in} + \bar{p}_{sn}. \quad (19)$$

The reduced force coefficients are obtained by dividing both sides of Eqs. (18) and (19) by the magnitude of the average momentum of the incident molecules. This normalization technique eliminates the singularity problems associated with the momentum accommodation coefficients, making the coefficients well-defined for all angles of incidence. Therefore, the tangential f_t and normal f_n reduced force coefficients are defined as

$$f_t = \frac{\bar{p}_{it} - \bar{p}_{st}}{\bar{p}_i}, \quad (20)$$

$$f_n = \frac{\bar{p}_{in} + \bar{p}_{sn}}{\bar{p}_i}. \quad (21)$$

Using Eqs. (18) and (19), the reduced force coefficients can also be written as

$$f_t = \frac{F_t}{N_i \bar{p}_i}, \quad (22)$$

$$f_n = \frac{F_n}{N_i \bar{p}_i}, \quad (23)$$

or using Eqs. (20) and (21) they can be written as

$$f_t = \sin \theta_i - \frac{\bar{v}_s}{\bar{v}_i} \sin \theta_s, \quad (24)$$

$$f_n = \cos \theta_i + \frac{\bar{v}_s}{\bar{v}_i} \cos \theta_s. \quad (25)$$

Equations (22) and (23) can be used to experimentally determine the reduced force coefficients from measurements of the forces exerted on surfaces by incident gases. The average velocity of the scattered molecules and the scattering angle can be expressed in terms of the reduced force coefficients using Eqs. (24) and (25) as

$$\bar{v}_s = \bar{v}_i \sqrt{(f_t - \sin \theta_i)^2 + (f_n - \cos \theta_i)^2}, \quad (26)$$

$$\theta_s = \tan^{-1} \left(\frac{\sin \theta_i - f_t}{f_n - \cos \theta_i} \right). \quad (27)$$

It is assumed that the average velocity of the scattered molecules is in the plane formed by the surface normal and the average velocity of the incident molecules. For specular scattering the reduced force coefficients reduce to

$$f_t = 0, \quad (28)$$

$$f_n = 2 \cos \theta_i, \quad (29)$$

while for diffuse scattering with complete thermal accommodation the coefficients reduce to

$$f_t = \sin \theta_i, \quad (30)$$

$$f_n = \cos \theta_i + \sqrt{\frac{\pi k T}{2 m \bar{v}_i^2}}. \quad (31)$$

By eliminating the singularity problems associated with the momentum accommodation coefficients, Eqs. (28)–(31) show that the reduced force coefficients do not range between zero for pure specular reflection and one for diffuse scattering with complete thermal accommodation. In fact, for the limiting case of diffuse scattering with complete thermal accommodation, the normal coefficient is a function of the angle of incidence, the temperature of the surface, the molecular mass, and average velocity of the incident molecules. Only for the case of specular scattering is one of the coefficients equal to a constant. Therefore, it is difficult to determine the degree of accommodation that takes place during a scattering process using only the reduced force coefficients. Since this quantity is of interest, a new parameter called the scalar momentum accommodation coefficient μ is introduced that does range between zero for pure specular reflection and one for diffuse scattering with complete thermal accommodation. The scalar momentum accommodation coefficient, given by

$$\mu = \frac{\bar{p}_i - \bar{p}_s}{\bar{p}_i - \bar{p}_d} = \frac{\bar{v}_i - \bar{v}_s}{\bar{v}_i - \sqrt{\pi k T / 2 m}}, \quad (32)$$

is defined using only magnitudes of the average momenta, thereby eliminating the functional dependence on the angle of incidence. Therefore, μ does not have the singularity problems associated with the momentum accommodation coefficients.

The energy accommodation coefficient α is another important quantity used to characterize gas-surface interactions [17], and is defined by

$$\alpha = \frac{\bar{e}_i - \bar{e}_s}{\bar{e}_i - \bar{e}_d}, \quad (33)$$

where \bar{e} is the average energy of the molecules. The energy accommodation coefficient is a measure of the thermal accommodation that takes place during a gas-surface interaction, and ranges between zero for specular reflection and one for diffuse scattering with complete thermal accommodation.

Also, since energy is a scalar quantity, the energy accommodation coefficient is well-defined for all angles of incidence.

The average energy of the incident molecules can change during a scattering process by a transfer of energy between the gas molecules and the surface, and/or by a change in the energy associated with the internal degrees of freedom of the gas. Detailed state-to-state measurements of the average energies associated with the internal-state distribution functions of the incident and scattered molecules can be difficult [1,2,5,8,23] and, in general, cannot be obtained from measurements of the forces exerted on surfaces by incident molecules. However, from a knowledge of the reduced force coefficients and the velocity distribution function of the incident molecules, the average translational energy of the scattered molecules can be accurately approximated for many applications.

The approximation method makes use of two types of energy accommodation coefficients. The definition of the first coefficient ϵ is based upon the average translational energies of the incident and scattered molecules and is given by

$$\epsilon = \frac{\bar{e}_{ik} - \bar{e}_{sk}}{\bar{e}_{ik} - \bar{e}_{dk}} = \frac{\bar{v}_i^2 - \bar{v}_s^2}{\bar{v}_i^2 - 4kT/m}, \quad (34)$$

where the subscript k represents the kinetic energy associated with translation, and \bar{v}^2 is the average of the velocity squared. The quantity $4kT/m$ is the average of the velocity squared of the scattered molecules assuming diffuse scattering from the surface with complete thermal accommodation. For applications where the energies associated with the internal degrees of freedom of the gas molecules can be neglected, ϵ is equal to the actual energy accommodation coefficient. The second coefficient ϵ' is defined using the average velocity of the incident and scattered molecules and is given by

$$\epsilon' = \frac{\bar{v}_i^2 - \bar{v}_s^2}{\bar{v}_i^2 - \pi k T / 2 m}. \quad (35)$$

Note that both ϵ and ϵ' range between zero for pure specular reflection and one for diffuse scattering with complete thermal accommodation. With the approximation that ϵ and ϵ' are equal,

$$\bar{v}_s^2 = \bar{v}_i^2 - \epsilon' (\bar{v}_i^2 - 4kT/m). \quad (36)$$

With a knowledge of the reduced force coefficients and the velocity distribution function of the incident molecules, the quantities \bar{v}_i^2 , \bar{v}_s^2 , and ϵ' can be determined. Once these quantities are known, Eq. (36) can be used to determine \bar{v}_s^2 .

An upper bound can be placed on the error introduced by equating ϵ' with ϵ . A simple calculation shows that the error can be written as

$$\left| \frac{\epsilon - \epsilon'}{\epsilon} \right| = \left| \frac{(\bar{v}_i^2 - \bar{v}_s^2)(1 - \epsilon) + \epsilon k T (4 - \pi/2)/m - (\bar{v}_s^2 - \bar{v}_i^2)}{\epsilon (\bar{v}_i^2 - \pi k T / 2 m)} \right|. \quad (37)$$

If measurements are made using molecular beams with relatively high Mach numbers, the velocity distribution function of the incident molecules is reasonably narrow. Thus, $\overline{v_i^2}$ is approximately equal to $\overline{v_s^2}$. With this assumption, the error can be expressed as

$$\left| \frac{\epsilon - \epsilon'}{\epsilon} \right| = \left| \frac{\epsilon kT(4 - \pi/2)/m - (\overline{v_s^2} - \overline{v_i^2})}{\epsilon(\overline{v_i^2} - \pi kT/2m)} \right|. \quad (38)$$

In the two limiting cases of specular reflection and diffuse scattering with complete thermal accommodation, the numerator in Eq. (38) is zero. Thus, it is reasonable to assume that for most applications $\overline{v_s^2} - \overline{v_i^2}$ is comparable to $\epsilon kT(4 - \pi/2)/m$, implying that

$$\left| \epsilon kT(4 - \pi/2)/m - (\overline{v_s^2} - \overline{v_i^2}) \right| \leq \frac{\epsilon kT}{m} (4 - \pi/2). \quad (39)$$

Thus,

$$\left| \frac{\epsilon' - \epsilon}{\epsilon} \right| \leq \beta, \quad (40)$$

where

$$\beta = \left| \frac{4 - \pi/2}{m\overline{v_i^2}/kT - \pi/2} \right|. \quad (41)$$

For N_2 incident upon SiO_2 -coated Kapton with an average velocity of 3180 m/s, β is approximately 0.02. Thus, the error introduced by equating ϵ' with ϵ is approximately 2%, and in fact is probably much less than 2% since the numerator in Eq. (38) is most likely much closer to zero than $\epsilon kT(4 - \pi/2)/m$. Equation (41) shows that for applications where $\overline{v_i^2}$ is much larger than $\pi kT/2m$ the error can easily be bounded by less than 1%. Also, Eq. (38) shows that the error is small for diffuselike scattering, assuming $\overline{v_i^2}$ and $\pi kT/2m$ are not equal. For specularlike scattering both ϵ' and ϵ are near zero, implying that $\overline{v_s^2}$ is approximately equal to $\overline{v_i^2}$. The small error introduced by equating ϵ' with ϵ can be contrasted with the simple assumption of equating $\overline{v_s^2}$ with $\overline{v_i^2}$ where errors can be as large as 60% for diffuselike scattering. Therefore, for many applications the average translational kinetic energy of the scattered molecules can be accurately approximated using Eq. (36).

To demonstrate the differences between the reduced force coefficients and the momentum accommodation coefficients, Figs. 2–5 show plots of the new coefficients and the macroscopic average quantities obtained from them for N_2 incident upon SiO_2 -coated Kapton with an average velocity of 3180 m/s. N_2 was accelerated to this average velocity using the seeded beam method [24] of expanding a gas mixture containing 5% N_2 and 95% H_2 through a supersonic nozzle source. Details of how the forces were determined with gas mixtures will be discussed in the section describing the interpolation method. Scanning electron microscope images revealed that the SiO_2 -coated Kapton had a microscopic surface roughness of less than 1 μm .

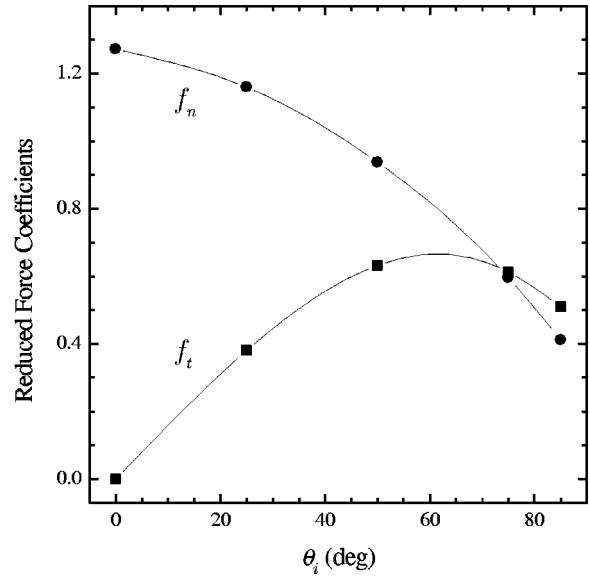


FIG. 2. The tangential and normal reduced force coefficients for N_2 incident upon SiO_2 -coated Kapton with an average velocity of 3180 m/s.

From Fig. 2 it can be seen that the reduced force coefficients are well behaved for all angles of incidence. As the angle of incidence increases past 45° , the tangential reduced force coefficient begins to decrease. This result implies that the scattering process becomes more specular at large angles of incidence. Figure 3 shows that as the angle of incidence increases past 45° the magnitude of the average velocity of the scattered molecules significantly increases. It can be seen from Fig. 4 that the scattering angle steadily increases as the angle of incidence increases. The results shown in Figs. 3 and 4 also imply that the scattering process becomes more specular as the angle of incidence increases. The two accommodation coefficients μ and ϵ' , shown in Fig. 5, indicate that accommodation decreases as the angle of incidence in-

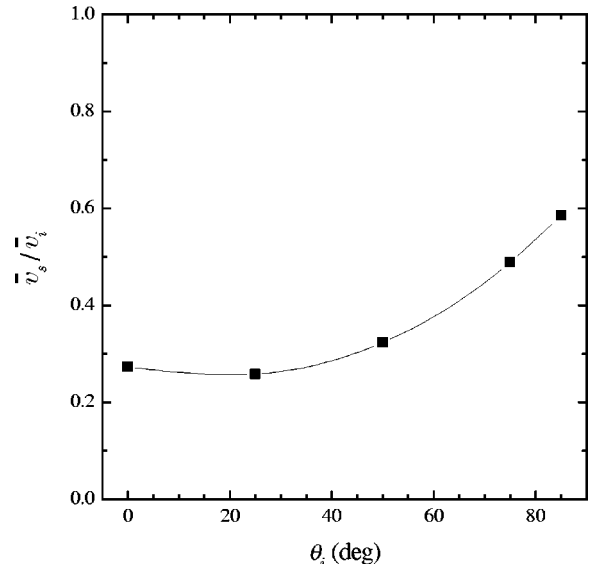


FIG. 3. The ratio of the average velocity of the scattered molecules to the incident molecules for N_2 incident upon SiO_2 -coated Kapton with an average velocity of 3180 m/s.

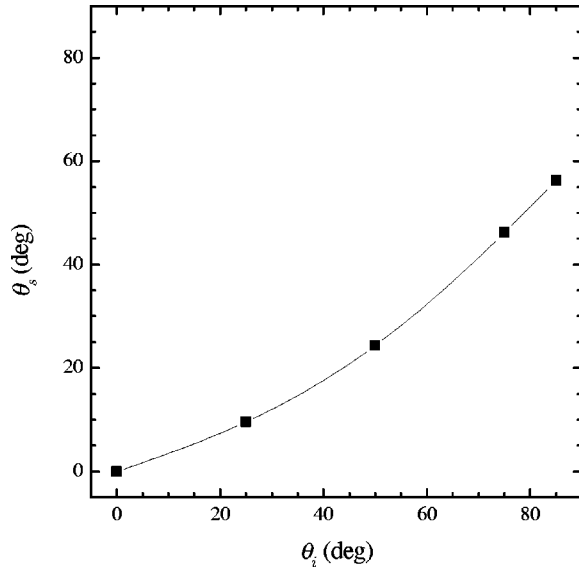


FIG. 4. The scattering angle for N_2 incident upon SiO_2 -coated Kapton with an average velocity of 3180 m/s.

increases. This result is also consistent with the scattering process becoming more specular for increasing angles of incidence.

IV. THE INTERPOLATION METHOD

Analyzing gas-surface interactions when molecules are incident upon a surface with a broad velocity distribution function requires a knowledge of the reduced force coefficients over the entire velocity range of the incident gas. This analysis can be dramatically simplified if values of the coefficients over the entire range of incident velocities could be interpolated from measured values at two widely separated incident velocities.

From Eqs. (24) and (25) it can be seen that the reduced force coefficients are independent of the incident flux. In

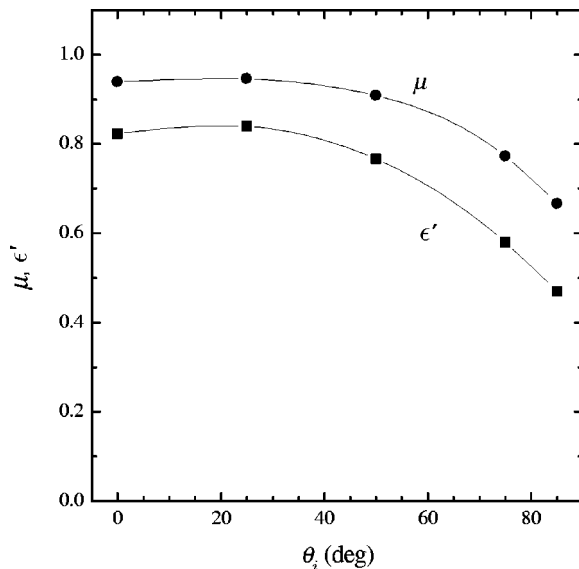


FIG. 5. The scalar momentum accommodation coefficient μ and the kinetic energy accommodation coefficient ϵ' for N_2 incident upon SiO_2 -coated Kapton with an average velocity of 3180 m/s.

general, the average velocity of the scattered molecules is a function of the magnitude and direction of the average velocity of the incident gas. However, for a fixed angle of incidence Eqs. (24) and (25) show that the reduced force coefficients are independent of incident velocity when \bar{v}_s is proportional to \bar{v}_i . Thus, for specularlike scattering the coefficients have a weak dependence on \bar{v}_i , and for near diffuse scattering with complete thermal accommodation the coefficients have the strongest dependence on \bar{v}_i . This result implies that if an interpolation method can be used to obtain accurate approximations of the reduced force coefficients for diffuselike scattering, then the method should yield even more accurate results for other types of scattering processes.

The reduced force coefficients were measured for N_2 incident upon Z-93-coated Al with an average velocity of 3180 m/s. Z-93 is a coating material used for thermal insulation on spacecraft surfaces. Scanning electron microscope images revealed that this surface was very rough on a scale greater than 10 μm . Molecules would be expected to scatter from this rough surface diffusely with near complete thermal accommodation, making this gas-surface interaction ideal for use in developing an accurate interpolation method.

The torsion balance used to measure the forces could not discriminate between the various gases simultaneously incident upon the scattering surfaces, but could only measure the total force exerted on the surfaces by all the gases. Therefore, to obtain the force exerted on the surface by the N_2 component in the seeded beam, the force due to the H_2 component had to be subtracted from the total force measured using the torsion balance. The force exerted by H_2 was determined from measurements of the reduced force coefficients for beams of pure H_2 incident upon the Z-93-coated Al surface with average velocities of 2590 m/s and 4620 m/s. In the seeded beam, H_2 had an average incident velocity of 3790 m/s. Approximate values of the reduced force coefficients for H_2 in the seeded beam were determined by linearly interpolating between the values in the measured coefficients. The results of this procedure are shown in Fig. 6. The experimental procedures used to determine N_i and \bar{v}_i for both H_2 and N_2 in the seeded beam are described elsewhere [16]. Equations (22) and (23) were then used to calculate the force exerted on the surface by the fraction of H_2 in the seeded beam. This approximate value for the force was subtracted from the total force measured using the torsion balance to obtain the force exerted by N_2 .

The results of this procedure are shown in Fig. 7, where the computed force components are compared to those expected for diffuse scattering with complete thermal accommodation. The graph shows that the predicted forces are very close to those expected for diffuse scattering with complete thermal accommodation. The tangential components are nearly identical (differences $< 4\%$) and the measured normal components are only slightly larger (differences $< 19\%$) at all incident angles. These results would imply that the gas scatters diffusely, but without complete thermal accommodation. More importantly, these results imply that differences between the values obtained using the interpolation method and the actual reduced force coefficients are small. Since the reduced force coefficients have the strongest dependence on \bar{v}_i for diffuse scattering with complete thermal accommoda-

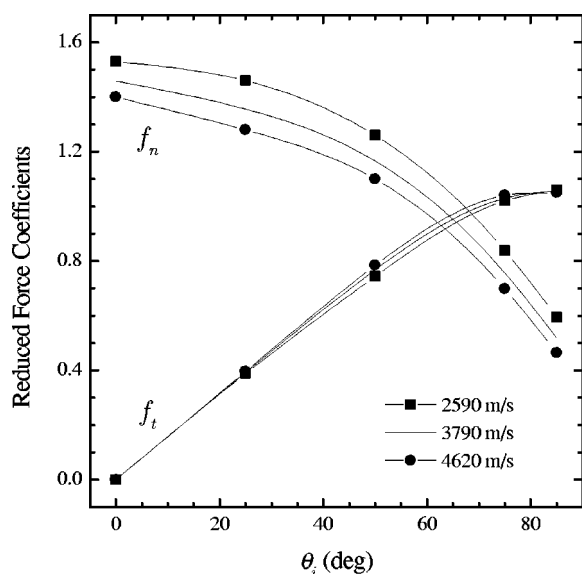


FIG. 6. The reduced force coefficients measured for H_2 incident upon Z-93-coated Al with average velocities of 2590 m/s and 4620 m/s. The reduced force coefficients for 3790 m/s, represented by the solid lines, were obtained using the interpolation method.

tion, such as the case for Z-93, even more accurate results would be expected for specularlike scattering.

In summary, the reduced force coefficients have been shown to solve the singularity problems associated with the momentum accommodation coefficients. It has also been shown that the reduced force coefficients can be used to calculate the magnitude and direction of the average velocity of the scattered molecules, and can be used to approximate the average translational kinetic energy of the scattered molecules. A simple interpolation method has been developed that can be used to obtain approximate values of the reduced force coefficients from measured values at widely separated

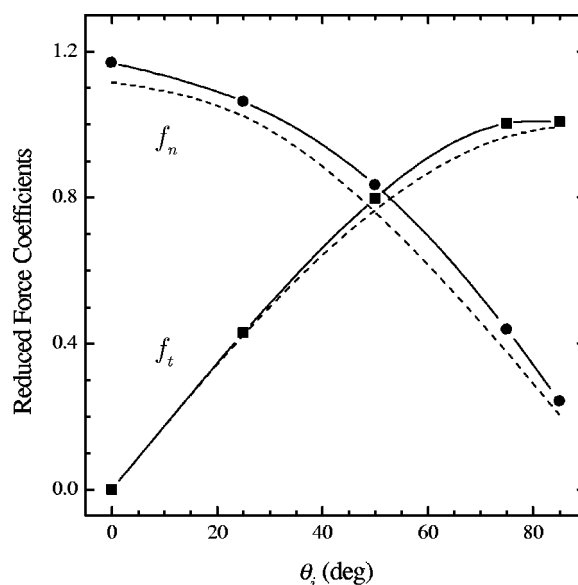


FIG. 7. The reduced force coefficients for N_2 incident upon Z-93-coated Al with an average velocity of 3180 m/s. The dashed lines indicate the tangential and normal reduced force coefficients if the incident gas scattered diffusely from the surface with complete thermal accommodation.

incident velocities. This result is a valuable simplification, from both an experimental and theoretical standpoint. Finally, the reduced force coefficients provide a new method to study gas-surface interactions due to the simplicity in which they can be used to predict both macroscopic and microscopic properties of molecules scattered from surfaces.

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