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Effect of the Knudsen Number on Heat Transfer to a Particle Immersed into a Thermal Plasma

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The Knudsen effect on heat transfer to a particle exposed to a thermal plasma is important for many practical situations experienced in plasma chemistry and plasma processing. This paper provides theoretical results of this effect based on the "heat conduction potential jump" approach. It is shown that a correction factor which depends on the Knudsen number must be introduced into the expressions for heat fluxes obtained previously based on the continuum approach. The Knudsen effect is stronger for smaller particles and it is also more pronounced for an Ar–H_2 plasma (compared to Ar and nitrogen plasmas at the same temperature). Since the Knudsen effect depends on the surface temperature of a particle, calculation of particle heating becomes more complicated.

KEY WORDS: Knudsen effect; heat transfer; small particles; thermal plasmas; analytical studies.

1. INTRODUCTION

The Knudsen effect on heat transfer to a body immersed into a rarefied gas is a well-known problem. There have been numerous theoretical and experimental investigations devoted to this subject. Excellent summaries are given in Refs. 1–3. The governing parameter which specifies the range in which the Knudsen effect plays an important role is the Knudsen number defined as

$$\text{Kn} = \lambda / L$$

where λ is the mean free path of the molecules, and L is a characteristic length of the body in question.

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Only when the Knudsen number is very small does the usual continuum approach used in fluid mechanics and heat transfer apply, i.e., the Navier–Stokes equations and Fourier's heat conduction law with continuous boundary conditions may be used. The Knudsen effect can be entirely neglected for this limiting case.

For cases in which the Knudsen number is still small but not negligible, "slip flow" and "temperature jump" boundary conditions have to be employed in conjunction with the continuum equations and Fourier's law. In this situation the Knudsen number will appear in the expressions for the heat flux or the drag force as a parameter.

At high Knudsen numbers, the flow situation is known as "free molecular flow." For this limiting case, continuum concepts or Fourier's law are no longer applicable; another approach is necessary based on the kinetic theory of gases where the Knudsen number becomes the most important parameter.

Between the "temperature jump" regime and the "free molecular" regime, there is a transition region which does not lend itself to a theoretical treatment, although some useful approaches have been suggested.(4)

Approximate Knudsen number ranges corresponding to these different regimes may be specified as follows:(2)

$Kn < 0.001$	continuum regime
$0.001 < Kn < 0.1$	temperature jump (slip flow) regime
$0.1 < Kn < 10$	transition regime
$10 < Kn$	free molecular flow regime

It should be emphasized that it is the Knudsen number itself, not the absolute values of λ or L, which determines the degree of importance of the Knudsen effect or the "rarefaction" effect.

For heat transfer in a rarefied gas, higher Knudsen numbers are caused by the reduced gas pressure which is equivalent to a larger mean free path of the molecules (λ is approximately inversely proportional to the gas pressure), while the characteristic length L of the body under consideration is usually large. On the other hand, for many problems in plasma chemistry and plasma processing, higher Knudsen numbers are primarily caused by the extremely small particle sizes, although atmospheric pressure may prevail in the plasma reactor. For example, particles utilized for thermal plasma synthesis or plasma spraying are typically on the order of microns or tens of microns. The mean free paths of molecules in an atmospheric-pressure, thermal plasma, on the other hand, are also on the order of 1 to 10 μm, resulting in Knudsen numbers approaching one. Therefore, the

Knudsen effect will have a stronger influence on heat transfer in such situations.

So far almost all studies of heat transfer and flight trajectories of single particles immersed in a thermal plasma have been based on the common continuum approach, except for a few investigations. Honda *et al.*[5] reported experimental results of heat transfer to a fine wire exposed to a low-pressure plasma (500 Pa and 9000 K). Since $Kn > 10$ in this situation, the continuum approach is no longer valid for this case. Rykalin and co-workers[6] studied heating of submicron metallic particles in a hot gas, using a free molecular flow approach.

The Knudsen effect for heat transfer to a particle immersed in a thermal plasma within a Knudsen number range $0.001 < Kn < 10$ remains virtually unknown, although this effect is certainly of importance for many practical situations.

In order to fill this gap, a theoretical treatment similar to the "temperature jump approach" used in rarefied gas heat transfer will be developed in this paper, modified for thermal plasma conditions. The Knudsen number range within which this treatment is applicable is approximately $0.001 < Kn < 0.1$. However, it is expected that this "temperature jump" prediction can be extended into the transition regime of Knudsen numbers up to 0.8 because of the good agreement between theoretical predictions and experimental data for small temperature differences,[7] as will be demonstrated in a later part of this paper.

2. ASSUMPTIONS AND EQUATIONS

The assumptions used for this analysis are similar to those employed in a previous paper:[8]

1. The particle is exposed to a uniform-atmospheric-pressure plasma without relative motion between the particle and the plasma.
2. The heat transfer process is steady.
3. The particle is assumed to be spherical.
4. Free convection effects are neglected.
5. Radiation from and to the particle is neglected.

The effects of unsteady heating and radiation from and to a particle have been treated in a previous paper.[9] Evaporation or sublimation of a particle in a high-temperature plasma may have a strong effect on heat transfer,[8] but this effect will not be included in this paper in order to simplify the analysis.

With the foregoing assumptions, the governing equation for heat transfer to a particle can be written as

$$4\pi r^2\left(\frac{k}{c_p}\frac{dh}{dr}\right)=Q_0 \tag{1}$$

or

$$4\pi r^2\frac{dS}{dr}=Q_0 \tag{2}$$

where k is the thermal conductivity, c_p the specific heat at constant pressure, and h the specific enthalpy of the plasma. The quantity Q_0 is the total heat flux transferred to the spherical particle, and r is the radial coordinate from the center of the particle; S is the heat-conduction potential defined as

$$S=\int_{T_r}^{T} k\,dT=\int_{h_r}^{h}\frac{k}{c_p}\,dh \tag{3}$$

which can be treated as one of the plasma properties which is only a function of the plasma temperature for a given plasma in local thermodynamic equilibrium (LTE). Such data have been presented in graphical forms for three different types of plasmas in a previous paper.[8] In Eq. (3), T_r and h_r represent reference temperature and reference enthalpy, respectively.

For the cases to be treated in this paper ($0.001<\mathrm{Kn}<0.1$), Eqs. (1) and (2) are applicable for the whole region except for a small zone near the particle surface (within the temperature jump distance). Equations (1) and (2) can be used for the entire region up to the particle surface by taking temperature jump boundary conditions into account.

The boundary conditions for Eq. (1) are

$$r\to\infty,\qquad T=T_\infty \tag{4a}$$

$$r=r_s,\qquad T=T_g \tag{4b}$$

Condition (4a) corresponds to the limiting case for which the continuum approach is still valid, but condition (4b) contains the temperature jump effect at the particle surface. The quantity T_g in Eq. (4b) is the plasma temperature, which is different from the true wall temperature T_s due to the presence of the Knudsen effect. The difference T_g–T_s represents the temperature jump at the particle surface.

Following a procedure proposed by Maxwell for velocity slip conditions, Kennard[1] suggested the following expression for the temperature jump:

$$T_g-T_s=z\left(\frac{dT}{dr}\right)_s \tag{5}$$

where $(dT/dr)_s$ represents the temperature gradient at the particle surface obtained from Eq. (2) for $r = r_s$. The temperature jump distance, z, has been derived by Kennard[1] as

$$z = \left(\frac{2-a}{a}\right)\left(\frac{2\gamma}{1+\gamma}\right)\frac{\lambda}{\text{Pr}} \tag{6}$$

where a represents the thermal accommodation coefficient measuring the extent to which interchange of energy takes place when a plasma particle strikes the surface; Pr and γ denote the Prandtl number and the specific heat ratio, respectively.

Equations (5) and (6) are valid for cases of small temperature differences ($T_\infty - T_s < 50°\text{C}$, for example).

For studying heat transfer to a particle under plasma conditions, it is more expedient to use heat-conduction potentials instead of temperatures. By using the heat-conduction potential, exact solutions for heat transfer to a particle without and with evaporation have been obtained for the limiting cases for which the continuum approach is valid.[8]

By introducing the heat-conduction potential, we can transform Eq. (5) into

$$S_g - S_s = z^* \left(\frac{dS}{dr}\right)_s \tag{7}$$

where S_g is the heat-conduction potential corresponding to T_g, $(dS/dr)_s$ is the heat-conduction-potential gradient corresponding to $(dT/dr)_s$. In Eq. (7) z^* denotes the distance over which the heat-conduction potential jump occurs. An expression for z^* will be derived in the next section.

Corresponding to the boundary conditions (4a) and (4b), the boundary conditions for Eq. (2) may be written as

$$r \to \infty, \qquad S = S_\infty \tag{8a}$$

$$r = r_s, \qquad S = S_g \tag{8b}$$

The solution of Eq. (2) with the boundary conditions (8a) and (8b) is

$$Q_0 = 4\pi r_s(S_\infty - S_g) \tag{9}$$

By combining Eq. (7), (9), and (2), the latter for $r = r_s$, one finds

$$Q_0 = \frac{4\pi r_s(S_\infty - S_s)}{1 + (z^*/r_s)} \tag{10}$$

The total heat flux to a particle using the continuum approach is given by $Q_{0c} = 4\pi r_s(S_\infty - S_s)$.[8] Therefore, the ratio of the heat flux with Knudsen effect to that for Kn < 0.001 becomes

$$\frac{Q_0}{Q_{0c}}=\frac{1}{1+(z^*/r_s)} \tag{11}$$

Equation (11) shows that the Knudsen effect will always reduce the heat flux to a particle. Since Q_{0c} is known, Q_0 can be calculated if z^* is known. In the following, the dependence of z^*/r_s on the Knudsen number and on other parameters will be determined.

3. JUMP DISTANCE OF THE HEAT-CONDUCTION POTENTIAL

An expression for z^* as a function of various parameters including the mean free path length can be derived by using a procedure similar to that given by Kennard.[1]

If E_i denotes the energy transferred per unit area and unit time to the particle surface by the incident stream of particles from the plasma, E_r the energy retained by these particles after impact, and E_s the energy that this latter stream of plasma particles would carry away if they were in equilibrium with the surface at the temperature T_s, then the accommodation coefficient can be defined by

$$a=\frac{E_i-E_r}{E_i-E_s} \tag{12}$$

By using a procedure similar to that given by Kennard,[1] the difference between the energies E_i and E_s can be expressed as

$$E_i-E_s=\frac{1}{2}\left(\frac{dS}{dr}\right)_s+\frac{1}{4}\rho_s\bar{v}_s\left(\bar{c}_p-\frac{1}{2}R\right)(T_g-T_s) \tag{13}$$

where $\bar{c}_p$ represents the average value of the specific heat within the temperature range from T_s to T_g. But the gas constant R and the specific heat ratio $\gamma=c_p/c_v$ will be treated as independent of the gas temperature. The gas density at the surface temperature is ρ_s, and $\bar{v}_s$ is the average molecular speed at T_s.

Since $R=c_p-c_v$, $c_p/c_v=\gamma$, and $(T_g-T_s)=(S_g-S_s)/\bar{k}$, Eq. (13) transforms into

$$E_i-E_s=\frac{1}{2}\left(\frac{dS}{dr}\right)_s+\frac{1}{4}\rho_s\bar{v}_s\left(\frac{1+\gamma}{2\gamma}\right)(\bar{c}_p/\bar{k})(S_g-S_s) \tag{14}$$

The net energy transferred to the surface of a particle by the impinging gaseous particles is given by

$$E_{\mathrm{i}}-E_{\mathrm{r}}=\left(\frac{dS}{dr}\right)_{\mathrm{s}} \tag{15}$$

Substituting Eqs. (12) and (15) into (14), one finds

$$S_{\mathrm{g}}-S_{\mathrm{s}}=\left(\frac{2-a}{a}\right)\left(\frac{\gamma}{1+\gamma}\right)\left(\frac{4\bar{k}}{\rho_{\mathrm{s}}\bar{v}_{\mathrm{s}}\bar{c}_p}\right)\left(\frac{dS}{dr}\right)_{\mathrm{s}} \tag{16}$$

Comparing Eqs. (16) and (7), we see that the distance over which the heat-conduction potential jump occurs is

$$z^*=\left(\frac{2-a}{a}\right)\left(\frac{\gamma}{1+\gamma}\right)\left(\frac{4\bar{k}}{\rho_{\mathrm{s}}\bar{v}_{\mathrm{s}}\bar{c}_p}\right) \tag{17}$$

This equation will be modified for the particular case of small temperature differences between the particle surface and the gas far away from the particle. By introducing an expression for the gas viscosity at room temperature ($\mu=0.5\rho_{\mathrm{s}}v_{\mathrm{s}}\lambda$), and the definition of the Prandtl number ($\mathrm{Pr}=\mu c_p/k$), Eq. (17) reduces to

$$z^*=\left(\frac{2-a}{a}\right)\left(\frac{\gamma}{1+\gamma}\right)\left(\frac{2}{\mathrm{Pr}}\right)\lambda \tag{18}$$

which is identical to that given by Kennard[1] for the temperature-jump distance. From Eq. (18) it follows that

$$\frac{z^*}{r_{\mathrm{s}}}=\left(\frac{2-a}{a}\right)\left(\frac{\gamma}{1+\gamma}\right)\left(\frac{4}{\mathrm{Pr}}\right)\mathrm{Kn} \tag{19}$$

where the Knudsen number is defined as

$$\mathrm{Kn}=\frac{\lambda}{d_{\mathrm{s}}}=\frac{\lambda}{2r_{\mathrm{s}}} \tag{20}$$

The temperature-jump distance usually comprises several mean free path lengths.

Equation (17), which contains average values of k and c_p, is applicable for cases with large values of $T_\infty-T_{\mathrm{s}}$, whereas the validity of Eq. (18) is restricted to small temperature differences $T_\infty-T_{\mathrm{s}}$. Comparing these two equations, one can consider the group

$$\lambda^*=\frac{2\bar{k}}{\rho_{\mathrm{s}}\bar{v}_{\mathrm{s}}\bar{c}_p}\mathrm{Pr}_{\mathrm{s}} \tag{21}$$

as an effective mean free path of the gaseous particles within the temperature region from T_{s} to T_{g}, and the distance over which the heat-conduction-potential jump occurs can be expressed as

$$z^* = \left(\frac{2-a}{a}\right)\left(\frac{\gamma}{1+\gamma}\right)\left(\frac{2}{\Pr_s}\right)\lambda^* \tag{22}$$

or

$$\frac{z^*}{r_s} = \left(\frac{2-a}{a}\right)\left(\frac{\gamma}{1+\gamma}\right)\left(\frac{4}{\Pr_s}\right)\mathrm{Kn}^* \tag{23}$$

where

$$\mathrm{Kn}^* = \lambda^*/d_s = \lambda^*/2r_s \tag{24}$$

can be considered as an effective Knudsen number under plasma conditions. The average values of the thermal conductivity and the specific heat can be readily calculated as

$$\bar{k} = \int_{T_s}^{T_g} k\, dT/(T_g - T_s) = (S_g - S_s)/(T_g - T_s) \tag{25}$$

and

$$\bar{c}_p = \int_{T_s}^{T_g} c_p\, dT/(T_g - T_s) = (h_g - h_s)/(T_g - T_s) \tag{26}$$

It is obvious that Eqs. (21)–(26) will reduce to their counterparts if small temperature differences $(T_\infty - T_s)$ are considered.

4. RESULTS AND DISCUSSIONS

By substituting Eq. (23) into relation (11), one obtains the following expression for the ratio of the heat flux with and without Knudsen effect:

$$\frac{Q_0}{Q_{0c}} = \frac{1}{1 + \left(\frac{2-a}{a}\right)\left(\frac{\gamma}{1+\gamma}\right)\left(\frac{4}{\Pr_s}\right)\mathrm{Kn}^*} \tag{27}$$

Calculated results for a particle immersed into an argon, an argon–hydrogen mixture (mole ratio 1:4), and a nitrogen thermal plasma are given in Figs. 1–3, respectively. In this paper, the same plasma properties which have been used in previous papers[8,9] are also employed. The wall temperature T_s is assumed to be 1000 K. The corresponding values of $\Pr_s$ and γ used in the calculation for the three types of plasmas are as follows:

	Argon	Ar–H_2	Nitrogen
$\Pr_s$	0.651	0.3799	2.287
γ	1.667	1.411	1.400

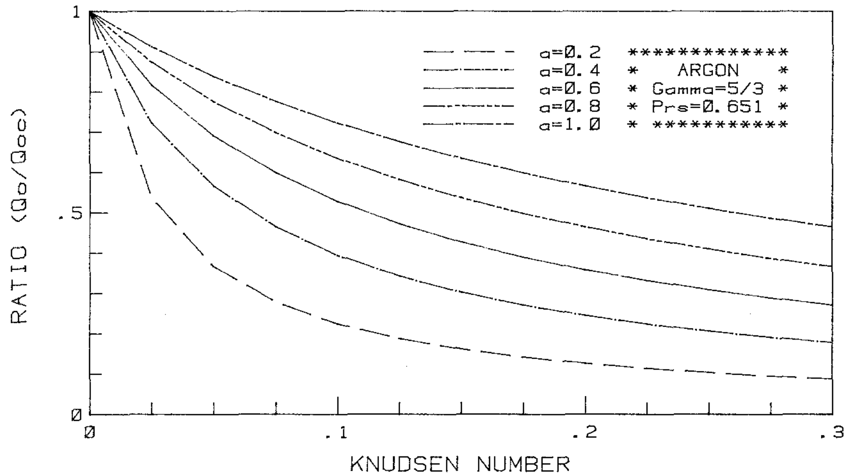

Fig. 1. Ratio of the heat flux with and without Knudsen effect as a function of the Knudsen number for an argon plasma ($T_s = 1000$ K, $\gamma = 5/3$, $Pr_s = 0.651$).

From Figs. 1–3 it is obvious that the Knudsen number Kn* has a strong effect on the heat flux to a particle exposed to a thermal plasma. The smaller the thermal accommodation coefficient, the stronger the Knudsen effect will be. The variations among the three different types of plasmas are primarily due to differences between the values of γ and Pr_s. The smaller Pr_s, the stronger the Knudsen effect will be.

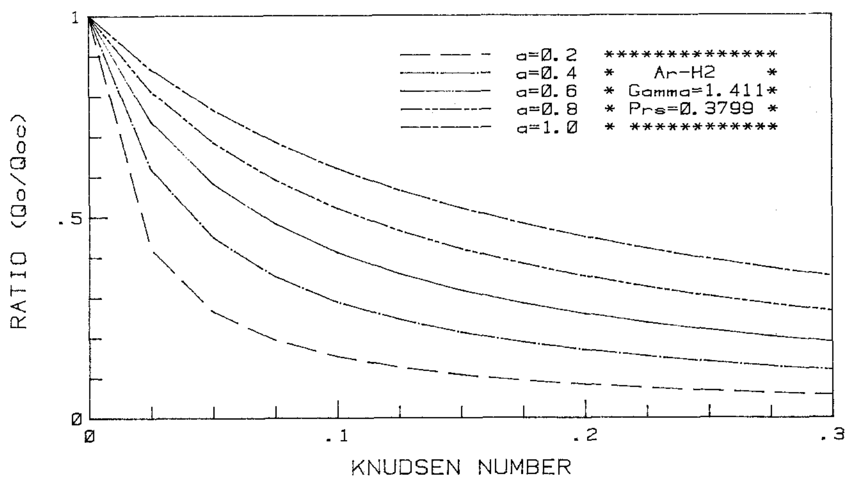

Fig. 2. Ratio of the heat flux with and without Knudsen effect as a function of the Knudsen number for an argon–hydrogen plasma (mole ratio 1 : 4; $T_s = 1000$ K, $\gamma = 1.411$, $Pr_s = 0.3799$).

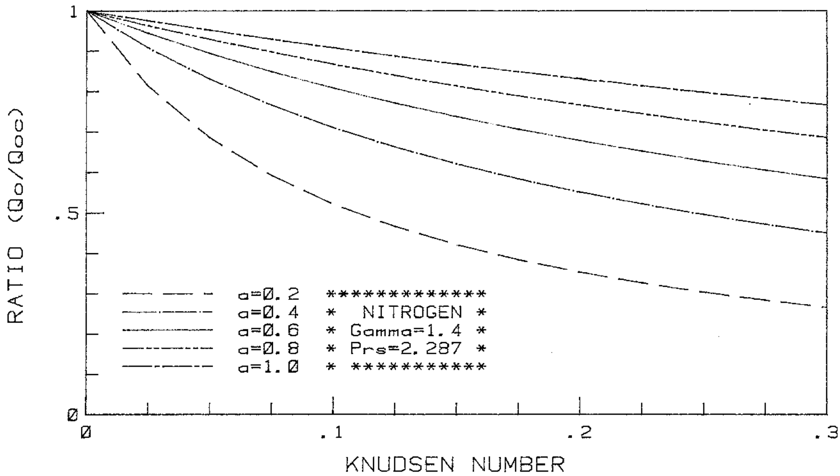

Fig. 3. Ratio of the heat flux with and without Knudsen effect as a function of the Knudsen number for a nitrogen plasma ($T_s = 1000$ K, $\gamma = 1.4$, $Pr_s = 2.287$).

In order to obtain a clear understanding of the Knudsen effect in practical situations, calculated results of Kn* for particles with different diameters are plotted in Figs. 4–6. Due to space limitations, only the results for a thermal accommodation coefficient of $a = 0.8$ are given, although the results for other values of the accommodation coefficient may be readily obtained.

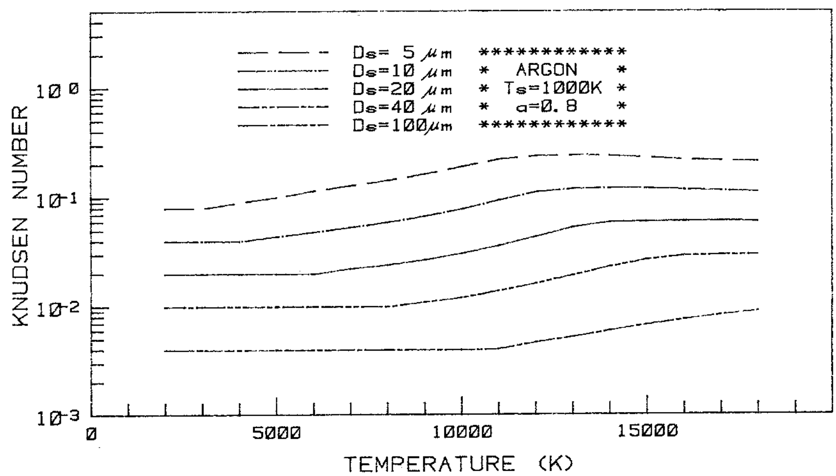

Fig. 4. Knudsen number for particles of different size in an argon plasma ($T_s = 1000$ K, $a = 0.8$).

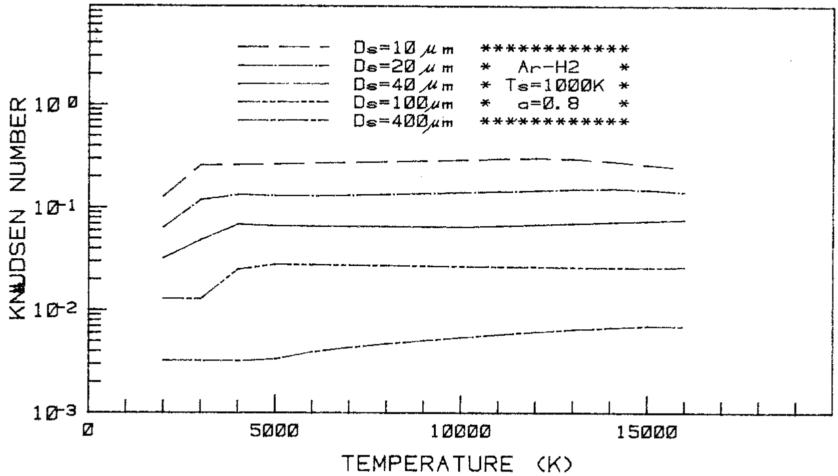

Fig. 5. Knudsen number for particles of different size in an argon–hydrogen (mole ratio 1:4) plasma ($T_s = 1000$ K, $a = 0.8$).

Because the thermophysical properties of the plasma are all functions of the plasma temperature, some iterations are needed in order to calculate $\bar{k}$, $\bar{c}_p$, λ^*, Kn*, etc. The iteration process starts from values corresponding to the surface temperature of the particle. From Eq. (27), Q_0/Q_{0c} can be obtained, and since the heat flux for the case of Kn < 0.001 is known[(8)] $[Q_{0c} = 4\pi r_s(S_\infty - S_s)]$, Q_0 can be calculated. Next $(dS/dr)_s$ can be derived

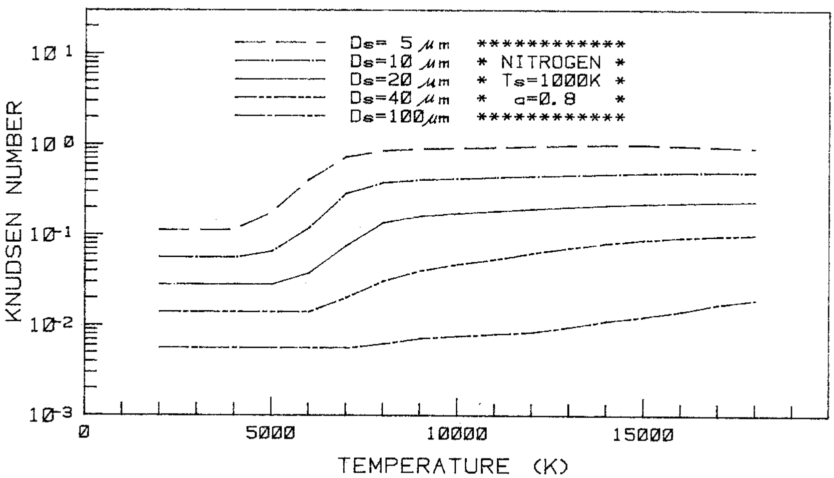

Fig. 6. Knudsen number for particles of different size in a nitrogen plasma ($T_s = 1000$ K, $a = 0.8$).

from Eq. (2) by setting $r = r_s$. The heat-conduction-potential jump follows from Eq. (7), and the corresponding temperature jump $(T_g - T_s)$ is obtained by using the known relation between S and T for a given plasma[8] and a given surface temperature T_s. From the given T_s and the calculated T_g, average values such as $\bar{k}$, $\bar{c}_p$, λ^*, Kn*, etc. can be calculated. By repeating the whole iteration process until convergent results are achieved, one finds Kn* and Q_0 for any given particle diameter and any given plasma.

For a given plasma, the effective Knudsen number Kn* depends mainly on the diameter of a particle, although it also varies with the plasma temperature. Since Kn* is larger for smaller particles, the Knudsen effect is more pronounced for smaller particles, as expected. The Knudsen number Kn* assumes larger values for the Ar–H_2 plasma than those found for Ar or N_2 plasmas although the other conditions are the same. Therefore, the Knudsen effect will be stronger for the Ar–H_2 plasma among the three thermal plasmas considered here.

Based on the calculated results of the effective Knudsen numbers in Figs. 4–6 and the relation (27) (Figs. 1–3), we obtain the ratio of the heat flux with and without Knudsen effect as a function of the plasma temperature for three types of plasmas and with r_s as a parameter (Figs. 7–9).

From Figs. 7–9 it is obvious that the Knudsen effect on heat transfer to a particle may be appreciable for many situations of practical importance, especially for smaller particles and for the argon–hydrogen plasma. For example, a particle of 20 μm diameter immersed into a plasma at 10,000 K experiences a reduction of heat transfer due to the Knudsen effect of

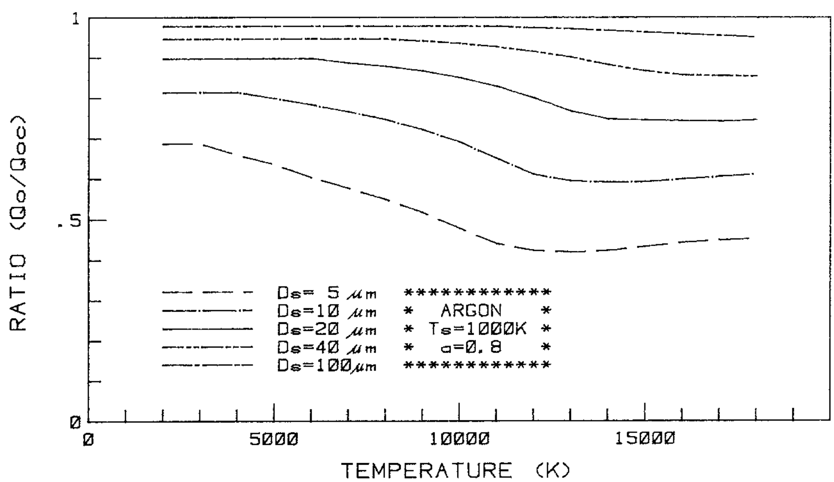

Fig. 7. Ratio of the heat flux with and without Knudsen effect for particles of different size in an argon plasma ($T_s = 1000$ K, $a = 0.8$).

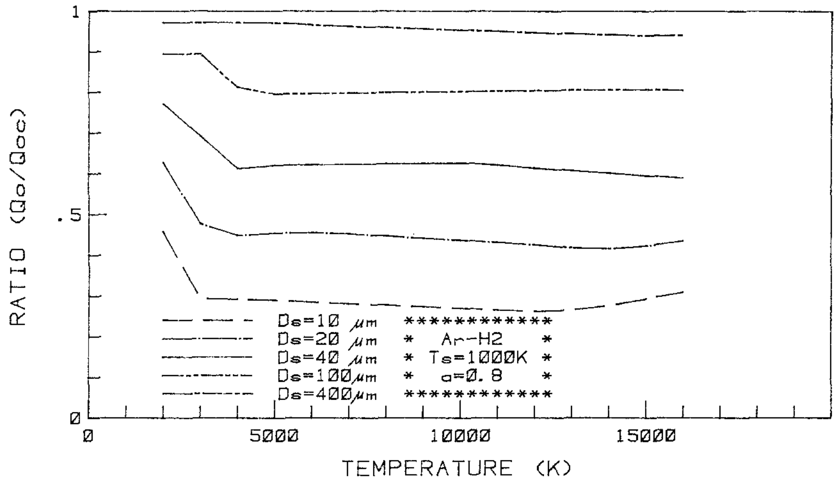

Fig. 8. Ratio of the heat flux with and without Knudsen effect for particles of different size in an argon–hydrogen plasma (mole ratio 1 : 4; $T_s = 1000$ K, $a = 0.8$).

approximately 15% in an argon plasma, approximately 56% in an Ar–H_2 plasma, and approximately 21% in a nitrogen plasma. The corresponding values for a 5-μm particle are: approximately 52% in an argon plasma, approximately 86% in an Ar–H_2 plasma, and approximately 58% in a nitrogen plasma. All these data refer to the case having an accommodation coefficient of 0.8. When the thermal accommodation coefficient decreases,

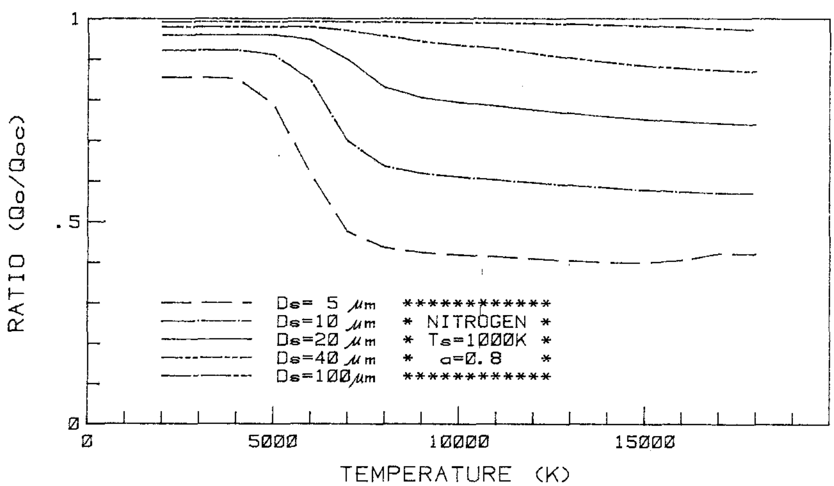

Fig. 9. Ratio of the heat flux with and without Knudsen effect for particles of different size in a nitrogen plasma ($T_s = 1000$ K, $a = 0.8$).

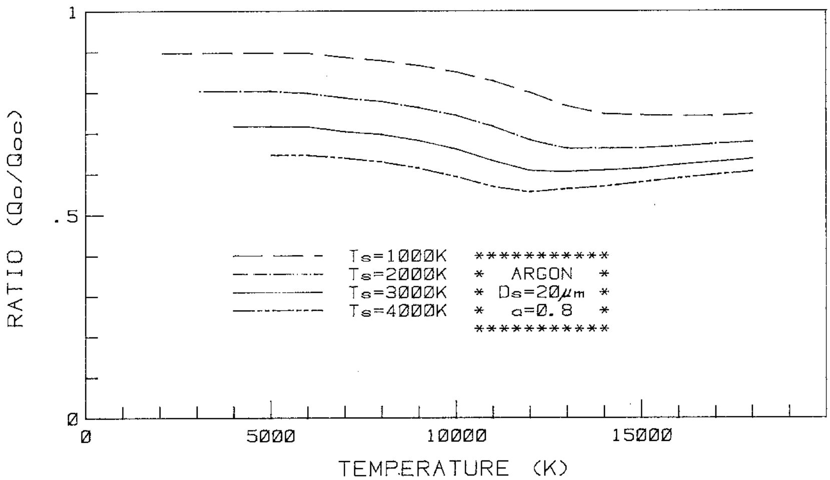

Fig. 10. Effect of the surface temperature of a particle on the ratio of the heat fluxes in an argon plasma ($d_s = 20\ \mu m$, $a = 0.8$).

the Knudsen effect will be even stronger. Unfortunately, almost no data on the thermal accommodation coefficient applicable to plasma heat transfer can be found in the literature. According to the usually accepted point of view, values close to 1.0 are appropriate for materials used in engineering. There is, however, serious doubt that this approximation holds for evaporating particles.

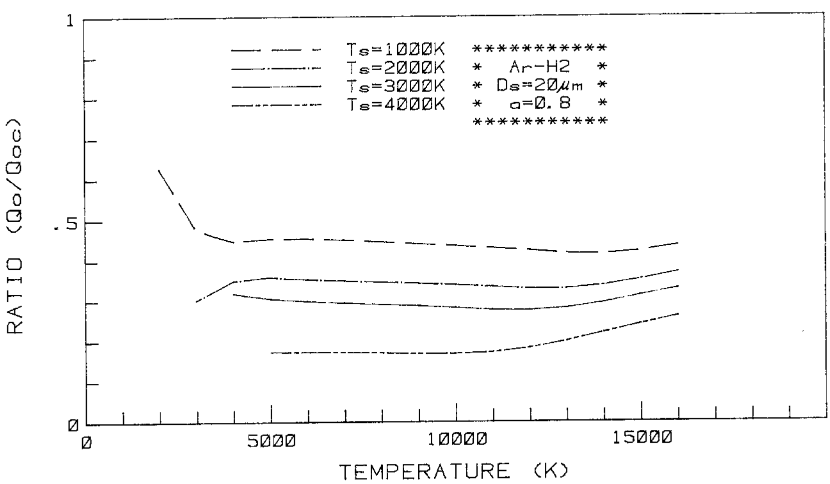

Fig. 11. Effect of the surface temperature of a particle on the ratio of the heat fluxes in an argon–hydrogen plasma (mole ratio 1:4; $d_s = 20\ \mu m$, $a = 0.8$).

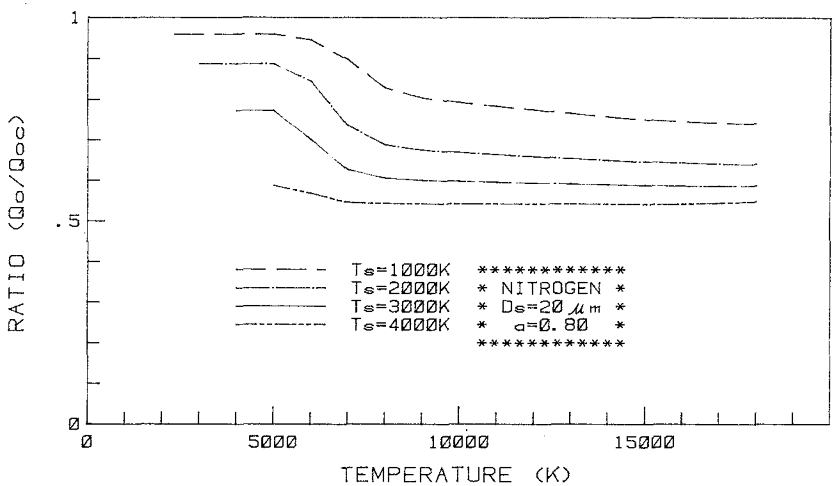

Fig. 12. Effect of the surface temperature of a particle on the ratio of the heat fluxes in a nitrogen plasma ($d_s = 20$ μm, $a = 0.8$).

Because the mean free path length of particles increases rapidly with temperature at lower temperature levels, it is expected that the Knudsen effect should depend on the surface temperature of the particle. Some calculated results for this effect are given in Figs. 10–12. As expected, the Knudsen effect is more severe at higher surface temperatures.

Inclusion of the Knudsen effect complicates the calculation of heat transfer to a particle immersed into a thermal plasma. In a previous paper[9] reduced times for heating, melting, and evaporation of a particle have been calculated for estimating the time periods required for executing the various processes. These reduced times are independent of the particle diameter for cases in which the Knudsen effect can be neglected. If the Knudsen effect on heat transfer has to be included, these reduced times can no longer be used, because the Knudsen effect depends on the particle diameter as well as on the surface temperature of the particle.

No experimental data on heat transfer to particles exposed to thermal plasmas are available for a direct check of the theoretical results given above. However, the experimental results reported by Takao[7] can be used to compare theoretical predictions for the limiting case of small temperature differences. Such a comparison is shown in Fig. 13. For a brass sphere in air,[7] taking a specific heat ratio $\gamma = 1.4$, a Prandtl number $Pr = 0.7$, and an accommodation coefficient $a = 0.8$, expression (19) may be used for calculating the heat transfer ratio with and without the Knudsen effect. Surprisingly, the agreement between experimental data and theoretical predictions is excellent, even for Knudsen numbers up to 0.84, suggesting

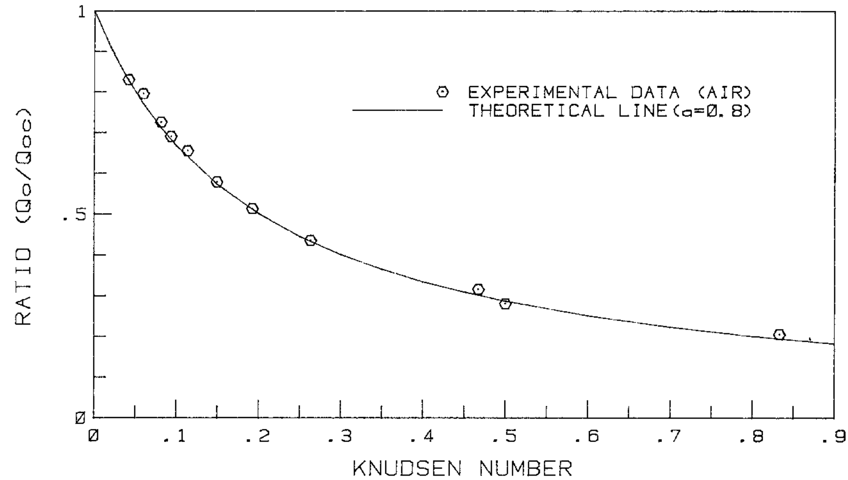

Fig. 13. Comparison of theoretical predictions with experimental data of Takao (Ref. 7) for small temperature differences ($a = 0.85$, $Pr = 0.7$, $\gamma = 1.4$).

that $a = 0.8$ is a reasonable value for the thermal accommodation coefficient. In addition, it seems that the approach based on temperature (or heat-conduction-potential) jump conditions may be extended to Knudsen numbers larger than 0.1 (≈ 0.8) without appreciable loss of accuracy.

5. CONCLUSIONS

The main conclusions of this study follow.

1. The Knudsen effect on heat transfer to a particle immersed into a thermal plasma may be important for many practical situations experienced in plasma chemistry and plasma processing.

2. Analytical expressions including the Knudsen effect are derived based on a "heat-conduction-potential jump" approach. The approximate region of the Knudsen numbers for which this analysis is applicable is in the range $0.001 < Kn < 0.1$.

3. The Knudsen effect is more severe for small particles and for particles with higher surface temperatures. Among three different types of plasmas under study (Ar, Ar–H_2, and N_2), the Knudsen effect is stronger for the plasma with the higher enthalpy.

4. Agreement of theoretical predictions with experimental data for the case of small temperature differences is excellent even for Knudsen numbers up to 0.84. This finding suggests that the "temperature jump" or "heat-conduction-potential jump" approach may be extended to Knudsen numbers exceeding 0.1 with reasonable accuracy.

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REFERENCES

1. E. H. Kennard, *Kinetic Theory of Gases*, McGraw-Hill, New York (1938), pp. 311–327.
2. F. M. Devienne, Low-Density Heat Transfer, in *Advances in Heat Transfer*, Vol. 2, J. P. Hartnett and T. Irvine, eds., Academic Press, New York (1965), pp. 271–356.
3. G. S. Springer, Heat Transfer in Rarefied Gases, in *Advances in Heat Transfer*, Vol. 7, J. P. Hartnett and T. Irvine, eds., Academic Press, New York (1971), pp. 163-218.
4. L. Lees, Kinetic Theory Description of Rarefied Gas Flow, *J. Soc. Ind. Appl. Math.* **13**, No. 1, 278–311 (1965).
5. T. Honda, T. Hayashi, and A. Kanzawa, Heat Transfer from Rarefied Ionized Argon Gas to a Biased Tungsten Fine Wire, *Int. J. Heat Mass Transf.* **24**, No. 7, 1247–1255 (1981).
6. N. N. Rykalin, A. A. Uglov, Yu. N. Lokhov, and A. G. Gnedovets, Properties of Heating of Submicron Metal Particles in a Hot Gas, *High Temp.* **19**, No. 3, 404–411 (1981).
7. K. Takao, Heat Transfer from a Sphere in a Rarefied Gas, in *Advances in Applied Mechanics, Supplement 2* (*Proc. Third Rarefied Gas Dynamics Sympsoium*), Vol. 2, J. A. Laurmann, ed., Academic Press, New York (1963), 102–111.
8. Xi Chen and E. Pfender, Heat Transfer to a Single Particle Exposed to a Thermal Plasma, *Plasma Chem. Plasma Process.* **2**, No. 2, 185–212 (1982).
9. Xi Chen and E. Pfender, Unsteady Heating and Radiation Effect of Small Particles in a Thermal Plasma, *Plasma Chem. Plasma Process.* **2**, No. 3, 291–314 (1982).