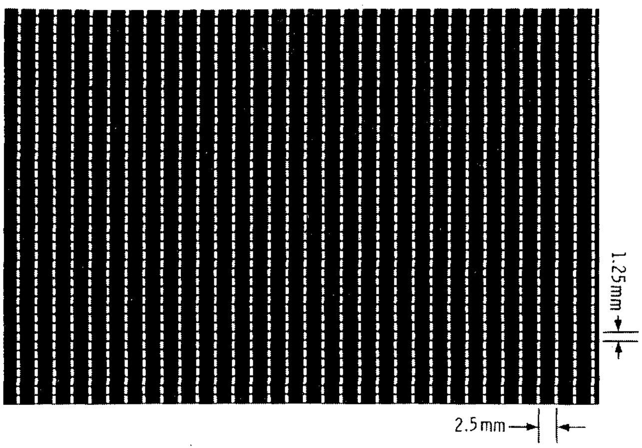

Fig. 1 Mesh patterns. The small connecting black lines are the bridgewires.

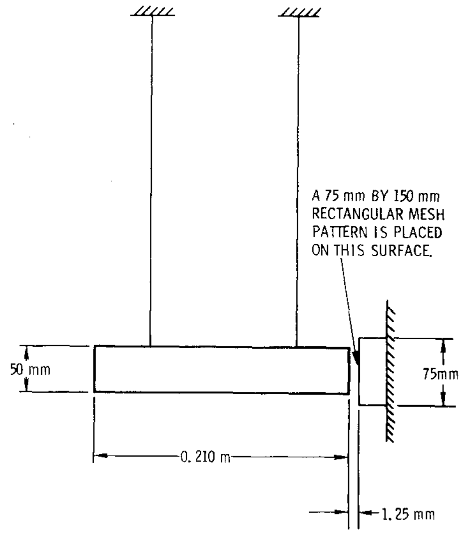

Fig. 2 Experimental arrangement.

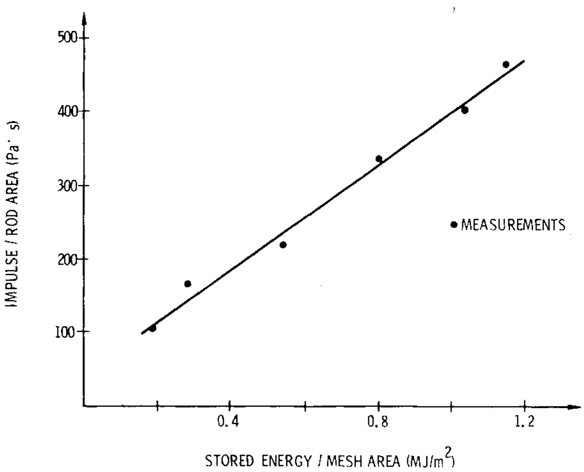

Fig. 3 Impulse vs stored energy.

Acknowledgment

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Hypersonic Free-Molecular Heating of Micron Size Particulate

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Nomenclature

M_∞ = Mach number
s = speed ratio = $M_\infty \sqrt{\gamma}/2.0$
T = ambient gas temperature
T_w = particles surface temperature
$\bar{\alpha}$ = thermal accommodation coefficient
γ = ratio of specific heats
σ = surface tangential reflection coefficient
σ' = surface normal reflection coefficient

THE purpose of this Note is to show experimental proof that the free-molecular derivations for Stanton number, recovery factor, and drag are indeed sufficient to compute the temperature and position time history of micron size particles in rarefield hypersonic gas flow. An application of this method would be to predict the observables of micrometeors or dust clouds entering the Earth's atmosphere at high altitudes.

A test program was conducted in the Hypervelocity Impact Range (SI) of the von Kármán Gas Dynamics Facility (VKF) at the Arnold Engineering Development Center (AEDC), to provide measurements of dust cloud temperature histories at pressure altitudes of nominally 30-μm Hg (the U.S. standard atmosphere equivalent of 72 km) and velocities of nominally 6.1 km/s.

A technique was worked out to launch at 10- to 20-mg "dust" cloud using a sabot fired from a gun barrel. After firing, the sabot was decelerated in the converging nozzle of the gun releasing the cloud. To further minimize the sabot's influence on the cloud it was deflected to impact in the blast tank. The dust cloud continued in flight through the 1220-cm long, 20.32-cm-diam range tank to impact on a styrofoam block. Three color radiometric measurements were made at approximately 0.4, 0.6, and 0.8 μm at three downrange stations. By then taking ratios of the observed intensities and using handbook values of emissivities, the time-dependent temperatures were calculated from Planck's radiation law.

The justification of using gas kinetics rather than continuum theory can be best appreciated by reference to Fig. 1 to see the typical size distribution, obtained using a Coulter machine, of silicon carbide particles used in one test.

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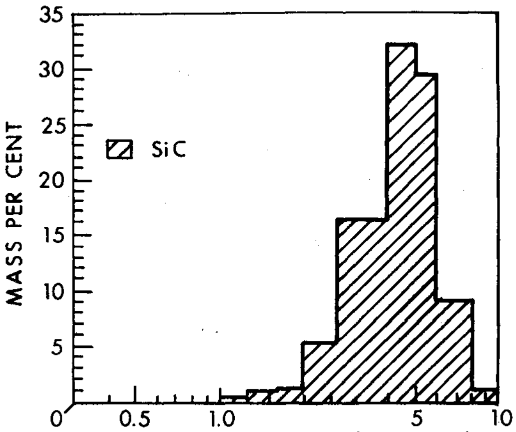

Fig. 1 Particle size distribution in test sample.

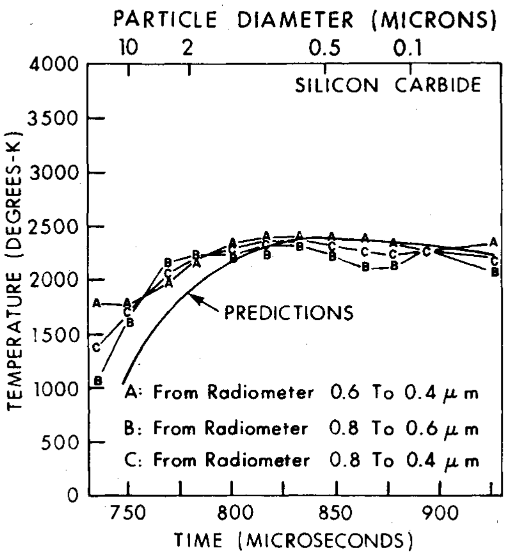

Fig. 2 Temperature measurements and predictions for station 1.

Although tungsten, tungsten carbide, and silicon carbide particles were used in the program, only the results for silicon carbide will be presented here to prove the point. Further test results can be found in Ref. 1. The ratio of the mean free path to the particle diameter, usually called the Knudsen number, was chosen as the governing criterion. For a 10-μm-diam particle we have a Knudsen number on the order of 100, obviously placing the entire sample tested well within the free-molecular flow regime.

Three assumptions were made in advance to make temperature predictions for the particles. First, the particles are assumed to be isothermal. In the general heat conduction equation the diffusivity, i.e., the ratio of conductivity to heat capacity, governs the rate of flow through a mass. Typical values of diffusivities for silicon carbide are of the order of 0.21 cm^2/s. The second assumption is that the published macroscopic emissivity curves of Ref. 2 are valid. Although a full Mie theory calculation may be dictated for particles falling below a certain size, the handbook values appear to give good temperature predictions. Third, although under a microscope the SiC particles seem to be irregular angular fragments, the assumption of spherical shape was made to reduce the complexity of the mathematical model.

In order to make temperature predictions, a numerical scheme was set up to compute the drag, recovery factor, Stanton number, heating rate, and particle temperature as a function of time and distance. This needed to be done for many of the possible diameters present in a given test sample.

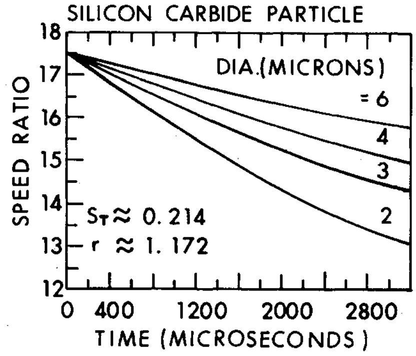

Fig. 3 Variation of range tank conditions with time.

During a test, once the cloud has been aerodynamically sorted out, each unit of measured time at a fixed point in the range tank is representative of only one possible diameter. The bigger particles would have arrived earlier and the lighter ones later. With this explanation the need of good drag calculation coupled with the heating is also apparent. The predicted temperature curve as seen at a particular station is drawn by joining the discrete points of temperature vs particle diameter using the observed time of arrival for proper spacing. The shape of this curve is shown in Fig. 2. For completeness, time is measured from zero just after the sabot leaves the gun barrel.

The complete free-molecular derivations of the aerodynamic coefficients are presented in Refs. 3 and 4. The integrated results for the sphere are

The Drag Coefficient

$$C_D = \frac{2-\sigma'+\sigma}{2s^3}\left\{\frac{4s^4+4s^2-1}{2s}\operatorname{erf}(s) + \frac{(2s^2+1)}{\sqrt{\pi}}e^{-s^2}\right\} + \frac{2}{3}\frac{\sigma'}{s}\sqrt{\frac{\pi T_w}{T}} \tag{1}$$

The Stanton Number

$$St = \frac{\bar{\alpha}(\gamma+1)}{8\gamma s^2}\left\{s^2 + s\ \operatorname{ierfc}(s) + \frac{1}{2}\operatorname{erf}(s)\right\} \tag{2}$$

The Recovery Factor

$$r = \frac{\gamma}{\gamma+1} \times \left\{\frac{(2s^2+1)[1+(1/s)\operatorname{ierfc}(s)] + [(2s^2-1)/2s^2]\operatorname{erf}(s)}{s^2[1+(1/s)\operatorname{ierfc}(s)] + (1/2s^2)\operatorname{erf}(s)}\right\} \tag{3}$$

Assuming completely accommodated scattering, the predictions were made assuming $\bar{\alpha}=\sigma=\sigma'=1$. The tunnel gas was nitrogen and consequently has a specific heat ratio (γ) equal to 1.4.

The aerodynamic heating rate ($\dot{Q}$) found from the Stanton number and recovery factor is

$$\dot{Q} = (S_t)(A\rho_\infty V_\infty C_{p_\infty})(r\{T_t - T\} + T - T_w) \tag{4}$$

where the symbols A, ρ_∞, V_∞, C_{p_∞}, T_t are, respectively, the total surface area, the freestream density, the freestream velocity, the freestream specific heat at constant pressure, and the adiabatic stagnation temperature. Taking into account both the aerodynamic heating and radiation cooling the particle temperature is found using a fourth-order Runge-Kutta integration scheme.

Figure 3 shows a predicted variation of speed ratio, Stanton number, and recovery factor for both a 2- and 6-μm-diam

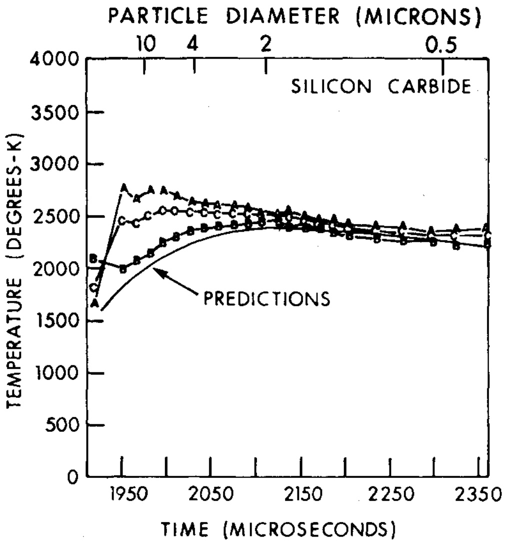

Fig. 4 Temperature measurements and predictions for station 2.

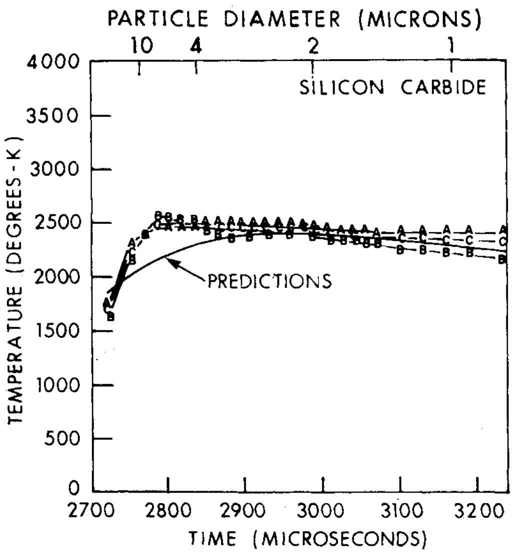

Fig. 5 Temperature measurements and predictions for station 3.

sphere for the actual test conditions. An x-ray photograph was used to obtain the initial launch velocity in the chamber.

Figures 2, 4, and 5 show the actual temperature computed using the observed radiometric data at the three stations. The time scale has been estimated to be ± 10 μs, while the temperature scale could have an error margin of ± 100 K. Superimposed on these is a smoother black line giving predictions. One sees from these figures that the analytical scheme used works well. Since the temperature dependent emissivity was thought to be the most uncertain of all theoretical input, both tungsten and tungsten carbide were also analyzed using the same free-molecular derivations, which also gave good agreement with experimental observations.

Acknowledgment

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Correlations among Turbulent Shear Stress, Turbulent Kinetic Energy, and Axial Turbulence Intensity

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Nomenclature

a,b,A	= constants
d	= pipe radius, half channel width
D	= pipe diameter
f	= function
U_b	= mean or bulk velocity
U_m	= maximum velocity
U_τ	= shear velocity
u,v,w	= fluctuating turbulent velocity components in the $x,y,$ and z, directions respectively
$\tilde{u},\tilde{v},\tilde{w}$	= root-mean-square values of $u,v,$ and w, respectively
y	= distance from the wall
R	= Reynolds number for a pipe defined as U_bD/ν
Re	= Reynolds number for a pipe defined as U_mD/ν
Re_c	= Reynolds number for a channel defined as U_md/ν
$\tilde{u}^+,\tilde{v}^+,\tilde{w}^+$	$=\tilde{u}/U_\tau$, $\tilde{v}/U_\tau$, $\tilde{w}/U_\tau$, respectively
$\overline{uv}^+$	$=\overline{uv}/U_\tau^2$
KE^+	= nondimensional turbulent kinetic energy $= \frac{1}{2}(\tilde{u}^{+2}+\tilde{v}^{+2}+\tilde{w}^{+2})$
y^+	$=yU_\tau/\nu$
ρ	= density
ν	= kinematic viscosity
τ_t	= turbulent shear stress $= -\overline{uv}\cdot\rho$

Subscripts

b	= bulk
c	= channel
m	= maximum
τ	= shear

Superscripts

$(\bar{\ })$	= time average of a quantity
$(\tilde{\ })$	$=[(\ )^2]^{\frac{1}{2}}$, root mean square

Introduction

THE relationship between the turbulent shear stress and the turbulent kinetic energy has been examined in the past. Harsha and Lee[1] studied such a relationship and suggested the following linear equation for the boundary-layer, jet, and wake flows:

$$\tau_t = A\,\tfrac{1}{2}(\overline{u^2}+\overline{v^2}+\overline{w^2}) \tag{1}$$

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Index category: Boundary Layers and Convective Heat Transfer—Turbulent.

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