Re-Entry Vehicle Stagnation Region Heat-Transfer in Particle Environments

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When re-entry vehicles encounter particles in the atmosphere, nosetip stagnation region heat transfer can be augmented significantly. The increase in heat transfer is attributed to turbulence generated by a coupling between particle/flowfield interactions and erosion-induced surface roughness and leads to an increase in nosetip stagnation region surface recession via the ablation process. In this work a heat-transfer model for hypersonic particle environments has been developed by extension of a freestream turbulence effects analysis. Application of the model to typical re-entry weather environments demonstrates that heating augmentation is dominated by surface roughness effects.

Nomenclature

D	= model diameter
f	= accommodation coefficient ($f \sim 0.3$ for erosive materials, 0.7 for nonerosive materials)
k	= roughness height
Q	= nondimensional turbulent energy
$\dot{q}$	= heat-transfer rate
T	= turbulence intensity
U	= velocity
dU/dx	= velocity gradient
β	= pressure gradient parameter
θ	= momentum thickness
μ	= viscosity
ν	= kinematic viscosity
ρ	= density
Subscripts	
e	= boundary-layer edge
p	= particle effects
r	= roughness effects
2	= behind the shock
∞	= freestream
0	= clear air

Introduction

TEST programs in two particle erosion wind tunnels[1,2] and in a ballistic range[3] have provided extensive evidence of augmented stagnation region heat transfer in hypersonic particle environments. This phenomenon first was observed when a titanium model ignited and burned at the Holloman test track even though anticipated heating rates for the given flow conditions including particle kinetic energy accommodation were thought to be insufficient to raise the model to the ignition temperature. Subsequent tests and analyses verified the presence of an augmented stagnation region heating, and the linear dependence of the heat-transfer rate with model wall temperature indicated a convective mechanism. Although it was known that erosion-induced surface roughness can effect an increase in convective stagnation region heat transfer,[4] the roughness contribution in the erosion wind-tunnel tests could not account for the measured heat transfer. Analysis of surface chemistry effects also indicated insufficient energy to account for the increased heating.[1]

Dunbar et al. correlated the available erosion wind-tunnel heat-transfer data in terms of a Stanton number as a function of the dust and surface debris to air mass flux ratio but offered no explanation for the success of this method. In order to interpret test results and to extrapolate confidently low Reynolds number ground test data to re-entry conditions, an understanding of the fundamental mechanisms responsible for augmented stagnation region heat transfer is required. Of particular concern is whether the erosion wind tunnels provide a realistic simulation of particle effects in flight environments.

The present work was undertaken to develop a phenomenological model of the augmented heating observed in erosion wind tunnels which then would be applicable to ballistic ranges and flight environments as well. Flowfield diagnostics (high-speed shadowgraph movies, laser holograms) employed in the wind-tunnel tests revealed that particle/flowfield interactions generate disturbances in the shock cap region,[5] and it is postulated that turbulence is the fundamental mechanism responsible for augmented stagnation region heat transfer. Examples of stagnation region convective heat-transfer augmentation due to freestream turbulence in subsonic flows abound in the

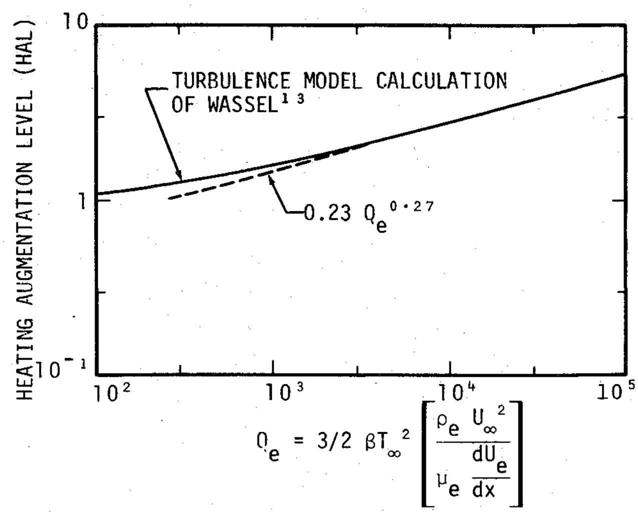

Fig. 1 Supersonic freestream turbulence effect on stagnation region heat transfer.

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literature.[6-8] Unpublished data[9,10] indicate a similar effect in supersonic flows. Recently Traci and Wilcox[11] and Wassel[12] have described the effects of subsonic freestream turbulence theoretically, and Wassel[13] has carried out an analysis of the effects of freestream turbulence in supersonic flows. In the present approach the supersonic freestream turbulence analysis of Wassel is extended to include particle and surface roughness effects.

Heating Augmentation in Erosion Wind Tunnels

Using a modified Kolmogorov-Prandtl turbulence model, Wassel has shown that the blunt body stagnation region heating augmentation level HAL (ratio of stagnation region heat transfer in a turbulent freestream to that in clear air) is a function of the nondimensional turbulent energy at the boundary-layer edge

$$Q_e = \frac{3}{2}\beta T_\infty^2 \left[\frac{\rho_e U_\infty^2}{\mu_e (\mathrm{d}U_e/\mathrm{d}x)}\right] \tag{1}$$

where the stagnation point pressure gradient parameter $\beta = 2\xi(\mathrm{d}U_e/\mathrm{d}\xi)/U_e$ in the Levy-Lees coordinates is ½ for axisymmetric stagnation points. Wassel's numerical solution (Fig. 1) is approximated by

$$\mathrm{HAL} = 0.23\, Q_e^{0.27} \tag{2}$$

for values of $Q_e \gtrsim 2000$. In the present approach, an equivalence between the effects of particles, surface roughness, and freestream turbulence is developed. Particle/flowfield interaction effects in erosion wind tunnels are treated first; surface roughness effects are modeled by analysis of existing rough wall heat-transfer data; and, finally, a technique is developed for coupling the particle, roughness, and freestream turbulence effects.

Particle/Flowfield Interaction Heating

Based on the qualitative indications from shadowgraphs and holograms and from surface pressure fluctuation measurements,[9] it is postulated that particles create turbulence through interaction with the stagnation region flowfield. Turbulence kinetic energy flux in the model stagnation region is taken to be proportional to the particle kinetic energy flux less the particle kinetic energy deposited in the form of thermal energy in the model

$$3/2\, \rho_2 U_2 (U')^2 \alpha\; 1/2\, \rho_p U_p^3 (1-f) \tag{3}$$

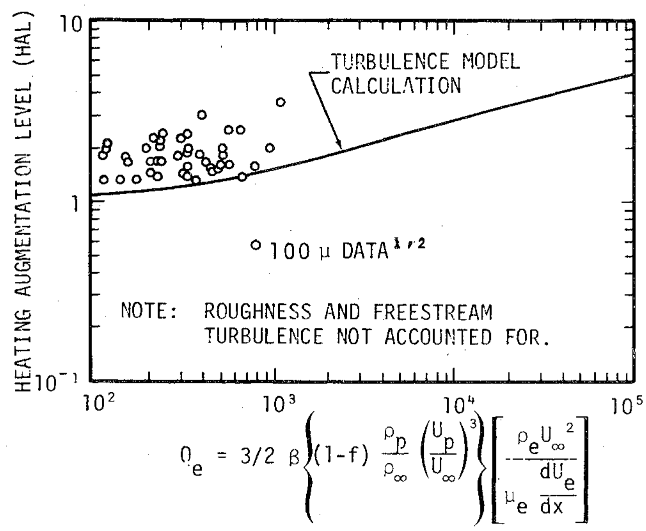

Fig. 2 Turbulence model prediction of particle/flowfield interaction heating.

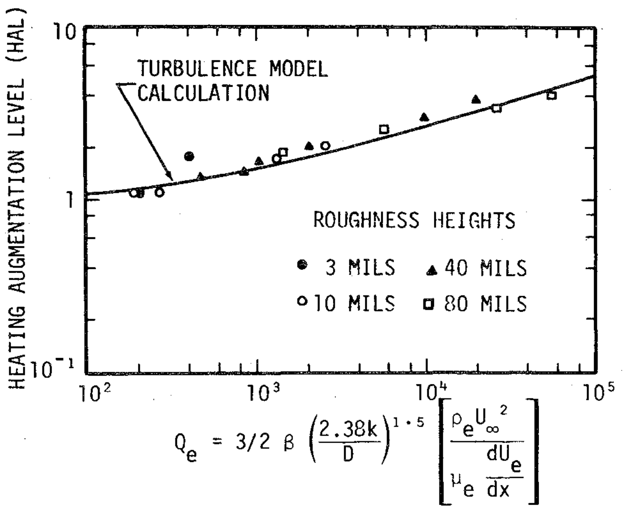

Fig. 3 Turbulence model prediction of PANT roughness heat-transfer data.[4]

Here the prime denotes the streamwise component of the fluctuating velocity term (assumed homogeneous). The equivalent freestream turbulence intensity is thus

$$T_p = A\left(\frac{\rho_p}{\rho_\infty}\right)^{1/2}\left(\frac{U_p}{U_\infty}\right)^{3/2}(1-f)^{1/2} \tag{4}$$

and the proportionality constant A to be determined from the data presumably will account for incoming and rebounding particles. In flight and ballistic range environments $U_p = U_\infty$, but in erosion wind tunnels the particles lag the flow.

A substantial bank of heat-transfer data exists from previous test programs[1,2] in the Arnold Engineering Development Center Dust Erosion Tunnel (DET) and the Boeing Hypersonic Wind Tunnel (BHWT). Models were 1- to 3-in.-diam hemispheres, Mach numbers were 5 to 9.5, and the freestream unit Reynolds numbers were 10^5 to 2×10^7/ft. Particle diameters were 50 to 800 μ with most of the data gathered for 100-μ-diam particles. Equation (4) was used with A set to 1 to compare with the heat-transfer data for erosion resistant (titanium) hemispheres in 100-μ particle flows since roughness effects would be minimized (Fig. 2). It was apparent, however, that the heat transfer was being influenced by surface roughness (4 to 6 mils) and possibly freestream turbulence, and that a coupled model was needed to explain the erosion wind-tunnel heat-transfer data.

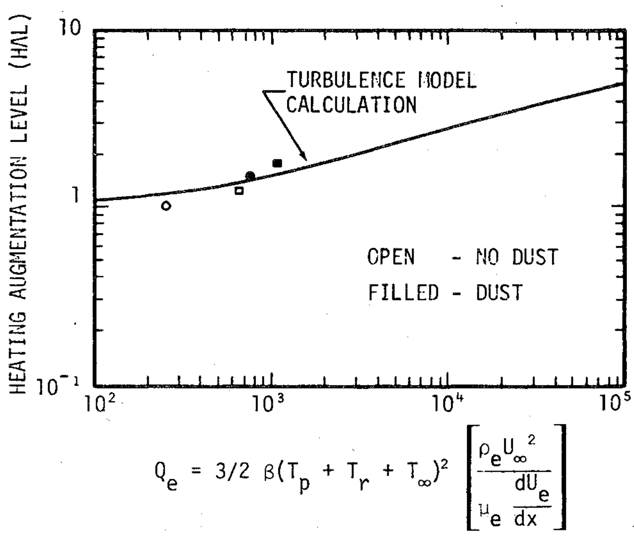

Fig. 4 Turbulence model prediction of coupled heat-transfer data.

Surface Roughness Heating

A series of experiments were carried out under the ABRES PANT program[4] to define the effects of surface roughness on heat transfer in the stagnation region. Clear air heat-transfer data were gathered for 5-in. diam models with controlled roughness over a Reynolds number range of 0.5 to 20×10^6/ft. The PANT roughness data are well represented by

$$\mathrm{HAL}_r = 0.19\left(\frac{\rho_2 U_2 D}{\mu_2}\right)^{0.2}\left(\frac{k}{\theta}\right)^{0.4} \tag{5}$$

and by comparison with Eqs. (1) and (2), an equivalent freestream turbulence intensity

$$T_r = 0.81\left(\frac{k}{\theta}\right)^{3/4}\left(\frac{\rho_2 U_2 D}{\mu_2}\right)^{0.15}\left[\frac{\mu_e (\mathrm{d}U_e/\mathrm{d}x)}{\rho_e U_\infty^2}\right]^{1/2} \tag{6}$$

can be defined. Using the hypersonic perfect gas approximations $U_\infty / U_2 = 6$, $\mathrm{d}U_e/\mathrm{d}x \simeq U_\infty / D$, $\rho_e = \rho_2$, $\mu_e = \mu_2$ with the momentum thickness

$$\theta = 0.245\sqrt{\nu_e/(\mathrm{d}U_e/\mathrm{d}x)}\,[1.4 - 0.4(T_w/T_e)] \tag{7}$$

Equation (6) can be reduced to

$$T_r \simeq (2.38k/D)^{3/4} \tag{8}$$

for the PANT test conditions, and the turbulence model accurately predicts the PANT data (Fig. 3). The excellent agreement between the model and the data supports the hypothesis that surface roughness influences stagnation region heat transfer through turbulence generation.

Coupled Effects Heating

Since both particle/flowfield interactions and surface roughness heating are thought to be caused by turbulence, it is necessary to determine how the turbulence levels combine in the presence of both mechanisms. To this end several tests were run in the DET in which preroughened (10- and 25-mil roughness) erosion-resistant titanium models were subjected to 100-μ particle flows. Heat-transfer measurements were made before, during, and after the dust runs. Both profilometer measurements and the clear air heat-transfer measurements assure that the 100-μ particles had not altered the model surface roughness significantly. Heating augmentation levels in the dusted flows were higher than could be accounted for by either the particle or roughness models individually and suggested a coupling between the two effects. Comparison of measured heat-transfer values with the turbulence model calculation indicated that the heating augmentation levels could be predicted best if the turbulence intensities (including freestream turbulence) were added linearly (Fig. 4).

By combining the effects of particle flowfield interactions, surface roughness, and freestream turbulence in the manner just prescribed, the turbulence model successfully predicts the 100-μ particle heat-transfer data for nonerosive (titanium) and erosive (graphite) hemispheres in the two erosion wind tunnels (Fig. 5). Erosive materials provide an increased convective heating agumentation level over nonerosive materials at the same flow conditions because of the difference in kinetic energy accommodation coefficient (0.3 vs 0.7) and because of the increased erosion roughness heights. Consistent with the approach used in the PANT study, the characteristic roughness height was taken as the peak-to-valley surface roughness measurement. The rms scatter in the test data about the turbulence model is 19% whereas the data scatter about the previously accepted correlation is 25%. More importantly, the turbulence model identifies the relative contribution of each mechanism which allows proper scaling to re-entry conditions. In addition, the present model provides an asymptotic reduction in augmented heating level as the particle concentration diminishes, and the weak power law exponent of Eq. (2) explains the observed heating augmentation insensitivity to model size. Although the turbulence model successfully predicts the wind-tunnel results for hemispheres, the physical basis for linearly combining turbulence intensities is uncertain, and the existing disc model heat-transfer data have not yet been explained successfully.

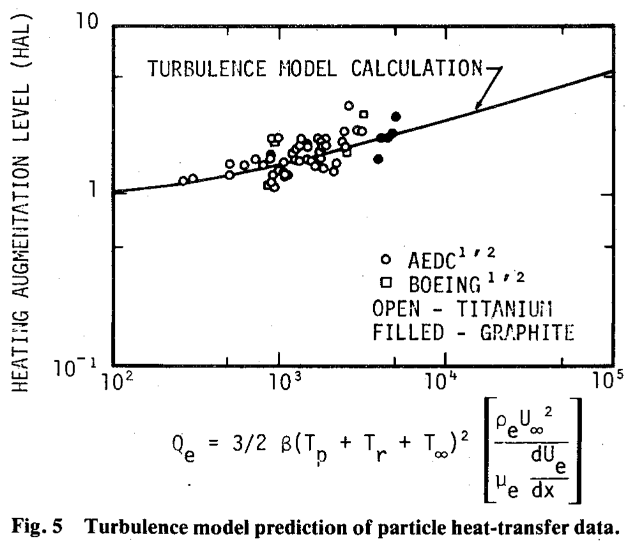

Fig. 5 Turbulence model prediction of particle heat-transfer data.

Extension to Flight Environments

In erosion wind tunnels the particle impact frequency is generally large enough (due to small particle sizes and high dust densities) that the model boundary layer is kept continually stirred up. However, in flight environments the time between particle impacts may be large compared to characteristic flowfield times, and the particle/flowfield interaction turbulence mechanism will be less effective. A relatively simple intermittency model describing this effect has been verified in a ballistic range.[3] An impact frequency parameter ϕ is defined as the ratio of time between particle impacts τ_2 to some characteristic flowfield time τ_I. It is assumed that the impact of each particle in the stagnation region (say in the sector bounded by the sonic point) creates the turbulence which when combined with the roughness-induced turbulence causes the heat transfer to be augmented by the factor $\mathrm{HAL}_{p,r}$. After a characteristic flow disturbance time $(\tau_I = D/U_\infty)$, the boundary-layer turbulence level returns to that induced by the roughness, and the heating augmentation drops to a level HAL_r caused by the roughness (Fig. 6). Defining the mean heating augmentation level as

$$\mathrm{HAL} = \frac{1}{\tau_2}\int_0^{\tau_2} \dot{q}_0 \,\mathrm{d}t \tag{9}$$

it follows that

$$\mathrm{HAL} = 1/\phi\,[\mathrm{HAL}_{p,r} + (\phi - 1)\mathrm{HAL}_r] \tag{10}$$

for $\phi \geq 1$.

Figure 7 demonstrates the intermittency effect in a ballistic range particle heat-transfer test where the impact frequency parameter $\phi = 111$, and the particle dispenser spacing has been accounted for.[3] Model stagnation point surface temperature is predicted by a transient heat conduction code using the present heat-transfer analysis. Particle kinetic energy effects are not sufficient to account for the measured surface temperature. With continuous heating augmentation, the model surface temperature is overpredicted; however, including the intermittency effect brings the prediction into good agreement with the data.

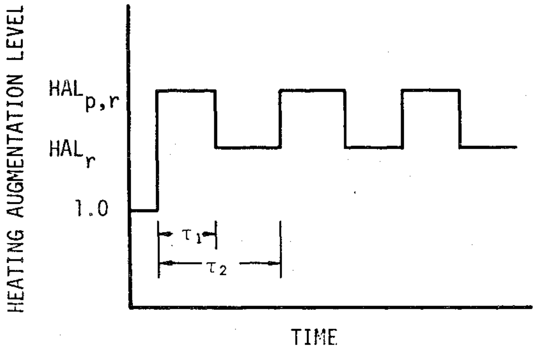

Fig. 6 Schematic of intermittent particle heating effects.

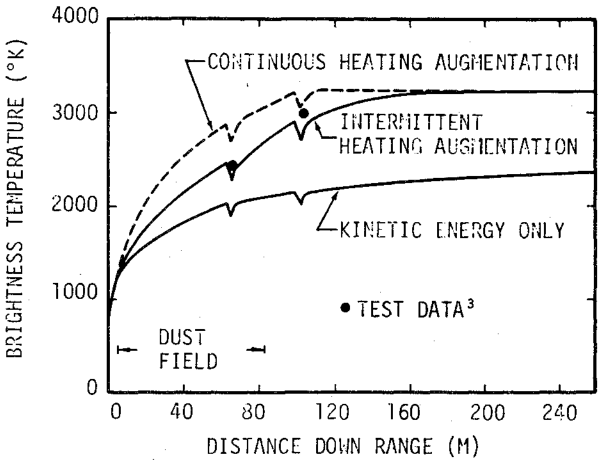

Fig. 7 Intermittency effect on stagnation region heat transfer in a ballistic range particle environment.

Re-entry vehicles can encounter particles in the atmosphere in the form of ice, snow, and rain precipitation layers with equivalent particle diameters ranging from 200 to 2000 μ. Heating augmentation levels in nominal weather environments range from 3 to 8 with the lower values occurring in cirrus ice layers (small particles) and the higher values due to large snowflakes. In an extensive parametric analysis it was found that the heating augmentation is dominated by surface roughness; in no case did the particle/flowfield interaction heating contribution exceed 15%. For the range of weather environments of interest to re-entry vehicle design $\rho_p/\rho_\infty < 10^{-3}$, $k/D > 10^{-2}$, and thus the ratio of roughness-induced turbulence energy to the particle/flowfield interaction turbulence energy is greater than 5 for erosive nosetip materials. Furthermore, $\phi >> 1$ except for cirrus ice layers where the particle density is low. Consequently, particle/flowfield interaction heat-transfer effects contribute very little to re-entry vehicle nosetip recession in most particle environments.

Summary and Conclusions

A unified turbulence model for re-entry vehicle stagnation region heat transfer in particle environments has been developed. The present approach constitutes an improvement over previous correlation procedures because it is based on a phenomenological model, reduces the scatter in the test data, brings together test data from two erosion wind tunnels, properly accounts for the observed heat-transfer insensitivity to model size, demonstrates the combined influence of particles and roughness, and provides an asymptotic reduction in augmented heating level as the particle concentration decreases to zero.

Whereas particle/flowfield interaction-induced heating augmentation is an important phenomenon in erosion wind tunnels in which the particle number densities are high, re-entry vehicle stagnation region heating augmentation in natural weather environments is dominated by surface roughness effects according to the present model. However, test data are limited to wind tunnels where the mass loss ratios are small in comparison with some re-entry environments. In severe erosion environments nosetip surface recession is primarily due to mechanical erosion; however, stagnation region heating augmentation remains an improtant phenomenon in that re-entry vehicle nosetip recession in light weather environments is dependent upon properly modeling the stagnation region ablation recession. Future efforts should concentrate on improving erosion roughness characterization and roughness heating augmentation modeling.

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