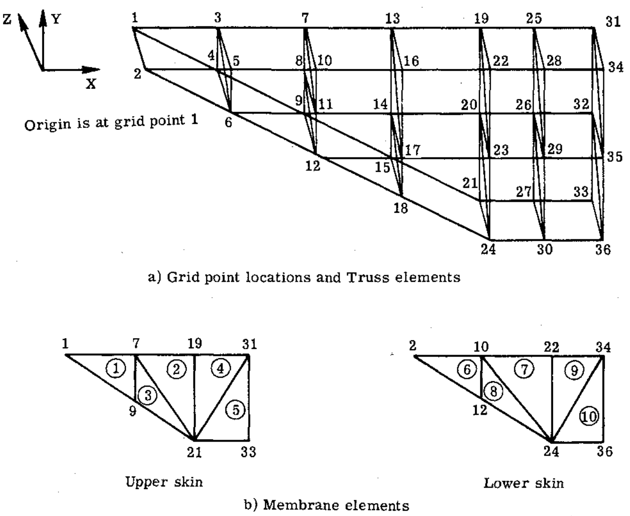

Fig. 1 Finite-element model of built-up wing.

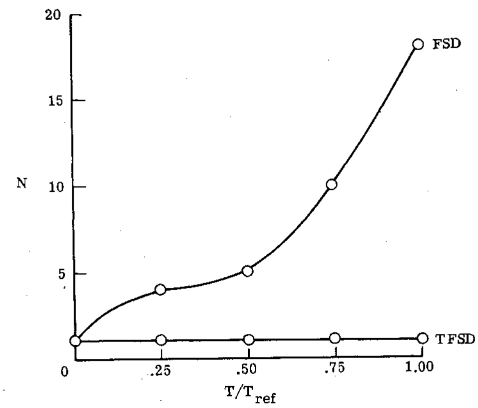

Fig. 2 Effect of thermal load level on convergence of FSD as compared to TFSD for sample problem. N = number of iterations for convergence within 5% of final mass.

single load case is applied and only strength constraints are enforced.[4] The largest proportion of the structural weight (80%) is represented in the membranes (skin). The thickest portions of the skin are represented by elements 4 and 5 in the upper skin and elements 9 and 10 in the lower skin as these are the regions of highest loading. Although the present procedure is based on sizing for strength and not deflections, the deflections of the final designs were within reasonable bounds. The maximum deflection occurred in the Z direction at grid point 33 and was about 5% of the wing semispan.

The significant result of these calculations from the standpoint of the efficiency of the TFSD algorithm is the relative number of iterations required by FSD and TFSD to converge from an initial trial design to within some arbitrary percentage (in this work 5%) of the final mass. TFSD achieved this degree of convergence in a single iteration for all four cases. The required number of iterations for FSD (N_{FSD}) is given in Table 1 and plotted in Fig. 2 against T/T_{ref} where T_{ref} represents the highest level of thermal loading. As expected, the performance of TFSD relative to FSD shows a strong increase as thermal loads measured by T/T_{ref} become larger.

Table 1 Effect of temperature on relative efficiency of FSD and TFSD for sample problem

Iterations	T/T_{ref}				
	0.	0.25	0.50	0.75	1.0
N_{FSD}	1	4	5	10	18
N_{TFSD}	1	1	1	1	1

For this example as well as for the examples of Ref. 4, thermal stresses are quite insensitive to structural sizing. The superiority of TSFD for these examples is associated with this insensitivity. This will be clear if we imagine a case where thermal stresses are completely independent of structural size is which case TSFD obviously would be superior. It seems reasonable that a broad range of structures will exhibit the relative insensitivity of thermal stresses to sizing. Consequently, the TSFD procedure should be widely useful for structures under combined thermal and mechanical loads.

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Stagnation Region Heat Transfer in Hypersonic Particle Environments

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Introduction

BLUNT bodies subjected to particle laden hypersonic flows can experience a stagnation region convective heat transfer significantly greater than in clear air. This phenomenon first was observed in an erosion wind tunnel when a titanium model ignited and burned even though flow conditions were thought to be insufficient to raise the model to the ignition temperature.[1] Subsequent test programs in two hypersonic wind tunnels provided further evidence of augmented heating in particle laden flows and indicated that heating rates are insensitive to model shape and size.[2,3] Dunbar, et. al., correlated the available heat-transfer data in terms of Stanton number as a function of the dust and debris/air mass flux ratio[3] but offered no phenomenological explanation for the success of this method. In order to interpret test results and to extrapolate confidently low Mach number, low Reynolds number ground test data[2,3] to reentry con-

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ditions, an understanding of the fundamental mechanisms responsible for augmented stagnation region heat transfer is required. Such a model is proposed here.

Particle/flowfield interactions have been observed to generate turbulence in the model shock cap region,[4] and it is postulated that turbulence is the fundamental mechanism responsible for augmented stagnation region heat transfer. Examples of convective heat-transfer augmentation caused by freestream turbulence in subsonic flows abound in the literature,[5-7] and, in fact, Galloway[6] suggested that particles influence the stability of the laminar stagnation region boundary layer in the same manner as freestream turbulence. Furthermore, both freestream turbulence and particle/flowfield interactions appear to require a pressure gradient to augment the convective heat transfer substantially. Recently, Traci and Wilcox[8] and Wassel[9] have described the effect of subsonic freestream turbulence on stagnation region heat transfer theoretically, using different turbulence models, and Wassel[10] has carried out an analysis of the effects of supersonic freestream turbulence. The present model of augmented stagnation region heat transfer in particle laden hypersonic flows is an extension of the supersonic freestream turbulence analysis of Wassel.

Model Development

A stagnation region heat-transfer model for particle laden flows was developed by analogy to the freestream turbulence analytical models and data correlations. Subsonic turbulence heat-transfer data have been calculated or correlated most successfully in terms of the parameter $T(Re_D)^{1/2}$ where T is the freestream turbulence intensity and Re_D is the Reynolds number based on model diameter.[5,6,8,9] This parameter evolves from the normalization of the turbulent boundary-layer equations in the stagnation region. Analytical approaches are apparently insensitive to turbulence model descriptions, since Traci and Wilcox[8] and Wassel[9] reproduce the subsonic heat-transfer data from the literature equally well using the Saffman turbulence model and a modified Kolmogorov-Prandtl turbulence model, respectively. Also, Galloway showed that calculated results are insensitive to eddy viscosity descriptions based on the law of the wall or a roll cell model. This modeling success and the insensitivity to approach suggests that the particle laden hypersonic flow heat-transfer data could be correlated in terms of a Reynolds number behind the shock (using the proper velocity gradient) and some equivalence between the particle flux and the turbulence intensity.

A more meaningful approach was developed by analogy to the supersonic freestream analytical model of Wassel.[10] By extending his subsonic results to supersonic flows, Wassel showed that the blunt body stagnation region heat-transfer augmentation level (ratio of stagnation region heat transfer in turbulent and clear air) is a function of

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

where T is the freestream turbulence intensity, ρ_e is the boundary-layer edge density, U_∞ is the freestream velocity, μ_e is the edge viscosity, and $\mathrm{d}U_e/\mathrm{d}x$ is the inviscid velocity gradient. The pressure gradient coefficient $\beta = (2\xi/U_e)(\mathrm{d}U_e/\mathrm{d}\xi)$ in the Levy-Lees coordinates is a constant for a given model geometry. Since particles in the shock cap region somehow must create the turbulence and since the particle/air mass flux ratio X has been shown to be a successful correlating parameter for nonerosive models,[3] it was assumed first that $T^2 \sim$ X. This approach successfully correlated heat-transfer data for values of X from 10^{-3} to 10^{-1}, model sizes of 1 to 3 in., Mach numbers of 6 to 9.5, and freestream Reynolds numbers of 10^5 to 2×10^7/ft (Fig. 1). The rms data scatter about the calculated curve is 24% whereas the scatter for the same data about the previous correlation[3] is 36%.

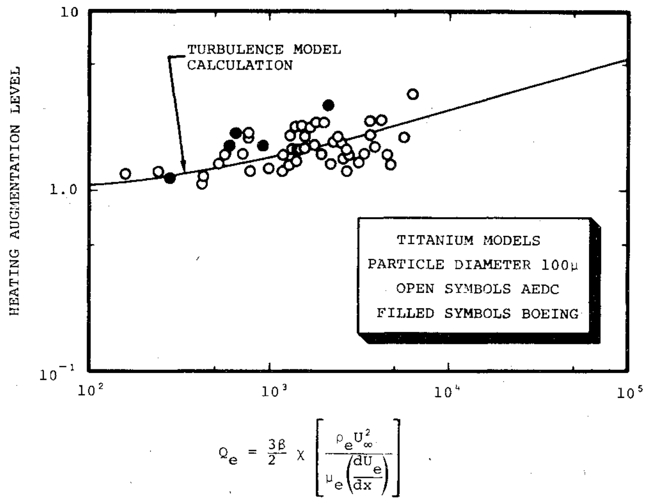

Fig. 1 Turbulence model prediction of dusted heat-transfer data.

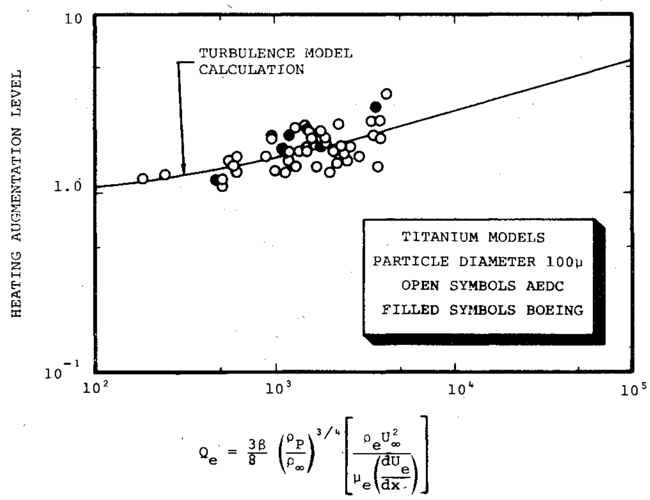

Fig. 2 Turbulence model correlation of dusted heat-transfer data.

Test data from the AEDC Dust Erosion Tunnel and the Boeing Hypersonic Wind Tunnel for titanium spheres are included in the figure. Test data for erosive materials (graphite, carbon phenolic) have been excluded because of the uncertain contribution of surface roughness.

Data Correlation

The calculated results of Wassel are presently available only in tabulated form. Although the tabular values could be curve fit, the polynomial approximation would be unwieldy for engineering use. It is apparent, however, from Fig. 1 that for $Q_e \gtrsim 200$ the calculated results can be approximated by a simple power law. The heat-transfer data were analyzed by multiparameter regression analysis which indicated that the data are best fit (Fig. 2) by setting $T^2 \sim (\rho_p/\rho_\infty)^{3/4}$. The resulting power law heat-transfer augmentation level correlation is

$$\mathrm{HAL} = 0.3 \left[3/8\beta (\rho_p/\rho_\infty)^{3/4} \frac{\rho_e U_\infty{}^2}{\mu_e (\mathrm{d}U_e/\mathrm{d}x)} \right]^{0.243} \tag{2}$$

and the data scatter is reduced to 20% about the correlation.

It is interesting to note that Eq. (3) can be reduced to

$$\mathrm{HAL} = 0.357[\beta (\rho_p/\rho_\infty)^{3/4} Re_{2D}]^{0.243} \tag{3}$$

with the perfect gas hypersonic approximations $(D_{eff}/U_e)(dU_e/dx) \simeq 1.1$, $U_\infty/U_2 \simeq 6$, and $\rho_e/\mu_e \simeq \rho_2/\mu_2$, where the subscript 2 designates conditions immediately behind the shock and D_{eff} is an effective model diameter. Equation 4 can be applied when the term in the brackets is greater than 70. This form of the correlation completes the analogy to the subsonic heat-transfer correlations and the power law exponent explains the generally observed weak heat-transfer dependence on model size.

Conclusions

A correlation of blunt model stagnation region heat-transfer data for particle laden hypersonic flows has been developed based on an analogy to the effects of freestream turbulence. Although the exact mechanism for turbulence production has yet to be determined, data correlation procedures indicate that the turbulence intensity is a function of the particle/air mass flux ratio. Insufficient variation in particle diameter is available in the heat-transfer data to determine if, for example, particle number flux is more meaningful. However, 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 facilities, properly accounts for the observed heat-transfer insensitivity to model size and, in its full form, provides an asymptotic reduction in augmented heating level as the particle concentration decreases to zero.

The present model was developed using dust laden hypersonic flow heat-transfer data for nonerosive materials so that surface roughness was not a contributing mechanism. It is postulated that the model can be extended to erosion roughened materials with the assumption that the erosion induced roughness elements generate turbulence through vortex shedding. Application of the erosion wind-tunnel results to reentry flight environments requires consideration of particle size effects (i.e. impact frequency) and erosive material contribution.

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Absolute Fluorine Atom Detection by Gasification of Boron Nitride

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Introduction

DISSOCIATION of fluorine, chlorine, and oxygen is known to increase the rates with which they gasify certain solids. Thus, for example, the rates of the F/W, F/Mo,[1] the Cl/Mo[2], and the O/graphite[2] reactions can be easily measured at temperatures below 1000K where the corresponding diatomic molecule reaction rates are negligible. These atom/solid gasification reactions could provide a gravimetric method for atom concentration measurement in flow systems, but at room temperature the atom reactions are so slow that complete reaction is difficult to achieve. This is not the case for the F/BN reaction, which we have employed to develop a gravimetric absolute F-atom detection technique as described in this Note.

Finely divided boron nitride reacts spontaneously with fluorine[3] at room temperature $P_{F_2} < 0.2$ atm according to the reaction

$$BN(s) + 1.5\, F_2(g) = BF_3(g) + 1/2 N_2(g) \tag{1}$$

with considerable heat release ($\Delta H°_{298} = -885$ kJ/mole).[4] However, we observe no reaction between dense, hot-pressed BN and F_2 at room temperature ($P_{F_2} \approx 6 \times 10^{-4}$ atm) although rapid BN gasification occurs if the fluorine is dissociated by a microwave discharge. BF_3 and N_2 need not be the only direct product species under nonequilibrium conditions. Some F-atoms may recombine, and BF(g), BF_2(g) may also be produced. Further, the reaction-induced temperature rise may increase the F_2 reaction rate. Therefore, although the F/BN reaction is rapid at room temperature, these side reactions might interfere with gravimetric F-atom concentration measurements. Our results show these problems to be absent under our experimental conditions. Also, limits are obtained on the intrinsic F, F_2/BN reaction rates which establish a wide range of applicability for this technique.

A previous example of F-atom concentration measurement by atom/solid gasification has been reported by Rosner and Allendorf.[1] They employed differences in the rates of atom and molecule reaction with Ti or B at high temperature to infer F-atom concentrations in partially dissociated fluorine. F-atom concentrations may also be measured using chemiluminescent titration with Cl_2[5-7] and spectroscopic techniques.[8] The present method avoids the need for specialized equipment and errors due to atom loss between the experiment of interest and the measuring device, which limit application of these alternate techniques. In fact, the need for measurements at higher total pressure and F-atom concentration, where the chemiluminescent titration fails,[7] motivated the present development.

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