Comparison Between Theory and Flight Ablation Data

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A theory for ablation of glassy materials under laminar and turbulent heating is verified by using data from an AICRM nose cone that was recovered after flight from a typical 5000-m scaffold with the spherical cap and cone in opaque quartz. The missile geometry is that of the Thor-Abile type, and the ablative material on the cone is a glassy polymer. Excellent agreement and numerical results are obtained. The actual value for the maximum ablated thickness along the sphere and cone is 9% higher than the theoretical value, whereas the weight loss of ablated material from the spherical nose and cone was only 7%. The transverse speed of ablated material which vaporized during re-entry is only 5% higher than the theoretical value. Most of the difference in the results can be explained by the effect of impurity material on the viscosity of opaque quartz.

Nomenclature

- A = body cross-sectional area
- Cp = drag coefficient
- h = specific heat at constant pressure
- g = acceleration, g
- u = velocity
- x = heat of vaporization
- Q = heat absorbed per unit mass of ablated material
- T = thermal conductivity
- e = reference temperature
- r = viscous law exponent
- P = pressure
- W = rate of heat transfer per unit area
- w = aerodynamic heat transfer rate per unit area to a hot, nonradiating wall
- \( v \) = aerodynamic velocity
- g = density of ablated material
- \( \rho \) = density
- \( \beta \) = density
- \( \gamma \) = Stefan-Boltzmann constant
- \( \tau \) = shear stress on nonslabbing surface
- \( \delta \) = required heat transfer rates with without mass injection

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*Numbers in parentheses indicate References at end of paper.
Table 1 Optical constants of opaque quartz

<table>
<thead>
<tr>
<th>Constant</th>
<th>Symbol</th>
<th>Value</th>
<th>Error</th>
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</thead>
<tbody>
<tr>
<td>refractive index</td>
<td>( n )</td>
<td>1.5</td>
<td>±0.1</td>
</tr>
<tr>
<td>effective surface reflectivity for internally produced radiation</td>
<td>( R_{0} )</td>
<td>0.2</td>
<td>±0.2</td>
</tr>
<tr>
<td>effective radiation mean free path</td>
<td>( \lambda = \alpha / a )</td>
<td>2.4 ( \times 10^{-8} ) ft</td>
<td>±0.7 ( \times 10^{-8} ) ft</td>
</tr>
<tr>
<td>ratio of effective radiation mean free path to mean free path between absorptions</td>
<td>( \alpha_{s} / \alpha_{a} )</td>
<td>0.15</td>
<td>±0.03</td>
</tr>
<tr>
<td>ratio of scattering mean free path to absorption mean free path</td>
<td>( \alpha_{s} / \alpha_{a} )</td>
<td>0.07</td>
<td>±0.03</td>
</tr>
</tbody>
</table>

*For detailed explanation of the meaning of these constants, see Ref. 23.*

The optical constants of opaque quartz are important in understanding the behavior of light as it passes through this material. The refractive index, effective surface reflectivity, and effective radiation mean free path are all critical in determining how light interacts with quartz. The ratio of these values helps in understanding the absorption and scattering properties of the material. These constants are fundamental in applications ranging from optical device design to environmental monitoring.
Effect of Unsteady-State Ablation

Nonsteady effects in the liquid layer are introduced only through the term $\theta/\theta t$ in the energy equation. The continuity and momentum equations are unaffected because of the incompressibility of the liquid and the smallness of the inertia forces as compared with the viscous forces. This unsteady effect has been considered for the conditions of zero radiation (24), but its extension to the radiation case is straightforward with an exponential temperature distribution.

Fig. 7 is a relative comparison for the steady and unsteady ablation velocities at the stagnation point for this flight case. It is found that, although the time history of the ablation velocities can be somewhat different, the total ablated thickness or area under the curves is about the same for steady and unsteady ablation. Hence, the effect does not introduce significant errors in the results for ablation thickness from the steady-state theory.

Other Effects

It is believed that there are no other sources of errors comparable in magnitude to the foregoing effects of viscosity and emissivity. The trajectory was calculated from accurate knowledge of the W/CD parameters and re-entry conditions. The effect of angle of attack or oscillatory motion of the body on the heating rates was neglected because these angles are usually small in the initial phase of significant aerodynamic heating. The turbulent heat transfer rates without mass injection have been verified from shock tube experiments (15,16), and mass injection does not reduce the turbulent heat transfer rates so effectively, as in the case of laminar boundary layers, which are better known.

Conclusions

The steady-state ablation theory for gasless materials, as reported in Ref. 2, predicts very accurately the ablation of opaque quarts under both laminar and turbulent heating, as confirmed from flight measurements of time integrals of ablation velocity, and a double integration with respect to time and space of the vaporization and ablation velocities.

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References