Generalized Nonequilibrium Binary Scaling for Shock Standoff on Hypersonic Blunt Bodies

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Introduction

The shock standoff distance δ, in a blunt-body stagnation region (Fig. 1), is sensitive to the thermodynamics within the shock layer and, hence, an important observable in hypervelocity impact facilities. Although numerical codes are available to predict δ, they are expensive for engineering parametric studies and do not yield physical insight or qualitative laws needed for experimental design and data interpretation. On the other hand, existing analytical methods may not permit extension to include multielement or high-temperature interaction. The present paper examines a new analytical theory of shock standoff with a nonequilibrium-distorted shock layer to demonstrate a generalized binary scaling property for high-altitude hypervelocity flight simulation work.

Theoretical Formulation

We consider a blunt nose region at zero angle of attack under the following assumptions: (1) The postshock static pressure is a known constant across the shock layer. 2. The tangential velocity component is of the form U = βUa, where β is an approximately defined constant equal to zero, which is the stagnation polar velocity gradient reflecting the shock variation. 3. Low Reynolds number viscous shock layer effects are negligible. For shock layer Reynolds numbers above 3000 (pertaining to many applications), these assumptions are sufficient to model the main aerothermal aspects of the flow along the stagnation line x = 0. Regardless of the gas or its chemistry, continuity yields the normal component of the velocity field as

\[ \rho(x) V(x) = (1 + J) \rho_0 \int_0^x \rho_0 \, dy \]

where J is a factor for two-dimensional or axisymmetric flow, respectively. When the density-gradient coordinate η is introduced,

\[ \eta = (1 + J) \frac{\rho}{\rho_0} \int_0^x \frac{\rho_0}{\rho} \, dy = 1 + J \frac{\rho}{\rho_0} \int_0^x \frac{\rho_0}{\rho} \, dy \]

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the r₂ vs ΔΩ variation is shown in Fig. 3b. For τ₀ > 1, it has a significant influence on r₂ by decreasing the relative non-equilibrium effect with increasing τ₀. However, when τ₀ ≥ 1, the r₂ vs ΔΩ correlation becomes insensitive to τ₀. Indeed, for τ₀ ≥ 1, a parametric effect is far smaller than the typical experimental data uncertainty, and thus, τ₀ may be regarded as a reliable parameter. In such cases, which may include a wide range of planetary entry vehicle conditions, so, thus, obtain the generalised binary scaling that the ratio r₂ depends only on ΔΩ regardless of the specific values of ω₂, R₂, U₂, and τ₀ or type of gas.

With regard to practical applications, the following simple cloudburst formula has been fitted to the curve (Fig. 3) throughout the entire non-equilibrium parameters:

\[ r_2 \approx \frac{3}{2} \left( 1 - \frac{3}{4} \frac{U_2}{V_2} \right) \left( \frac{R_2}{R_0} \right) \quad (11) \]

Equation (11) yields the linear function \( t \approx 1 - 0.702 \) in the nearly frozen limit \( ΔΩ < 1 \), and the inverse square \( √(t) \approx 0.702ΔΩ^{-1/2} \) for nearly equilibrium flow \( ΔΩ \rightarrow 1 \).

Conclusion

We have presented some new parametric study results from a viscous analytical theory of hypersonic blunt nose shock waves—which establish an extended nonequilibrium--disociation buoyancy scaling concept wherein the need to simulate flight velocity is eliminated when the parameter \( ρ_0 \) in \( D_2/2AD \) is greater than unity.

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References