Real Gas Laminar Boundary-Layer Separation Prediction Methodology

Hideo Ikawa*
Rockwell International, Downey, Calif.

Abstract

A REAL gas laminar boundary-layer separation methodology has been developed to predict Space Shuttle Orbiter control surface effectiveness during atmospheric entry. The methodology is based on the Lees-Klineberg moment integral theory. A real gas laminar boundary-layer model, having a binary atomic diffusion of frozen gas composition, is assumed. A brief discussion of theory and sample results are presented herein. A set of boundary-layer profile parameters which are required for this theory is given in the full paper.

Contents

The aerodynamic control surface effectiveness of the Space Shuttle Orbiter (SSO) during re-entry is strongly affected by the laminar flow separation induced by the compressively deflected surface. The SSO re-entry hypersonic control surface effectiveness (HCSE) estimates were initially based primarily on wind-tunnel test data. Extrapolation of test data to higher elevon/body flap deflections revealed that a potential control reversal phenomena may exist. However, the quality of test data was such that a definite control reversal trend could not be established.

A methodology for predicting the supersonic/hypersonic laminar boundary-layer separation for the ideal gas case has been developed and presented in Ref. 1. During re-entry, in the flight regime where aerodynamic forces become significant, inviscid air on the windward side of the SSO can be fully dissociated by compression heating. However, since the outer surface skin temperature of the SSO thermal protection system (TPS) will not exceed 2000 K, the neighboring dissociated air will recombine fully. Therefore, a dissociation-recombination cycle of the reacting gas is expected to be produced within the boundary layer, the contribution of which to the laminar flow separation mechanism is presently unknown.

Theory for Real Gas Flow Separation Prediction

The real gas flow separation prediction methodology, which is suitable for design applications, is derived from the ideal gas Lees-Klineberg Moment Integral Theory.[2] Since the analysis of multispecies gas having a finite reaction rate is too complex and not suitable for the integral theory method, an idealized binary reacting gas (molecule-atom of one species of gas) has been selected to represent the approximate behavior of a real gas. The binary-single-species reaction assumption is valid, because in the flight regime considered, one species of molecule is reacting while the others are in an equilibrium state. Furthermore, the transport properties of nitrogen and oxygen in air are quite similar; therefore, dissociating air can be modeled by an "effective dissociation energy" term.

In the real gas model formulation, it was assumed that atoms from the outer edge of the boundary layer are diffused toward the cooler wall and the recombined molecules are diffused away from the catalytic wall. The diffusion process within the boundary layer is assumed to be predominant over the finite chemical reaction rate process.

The Lees-Klineberg theory[1,2] is extended by including the conservation of species equation [Eq. (1)] and by modifying the right-hand side of the energy equation [Eq. (2)].

$$\rho u \frac{\partial \alpha}{\partial x} + \rho v \frac{\partial \alpha}{\partial y} = \frac{\partial}{\partial y}\left[\rho D_{12} \frac{\partial \alpha}{\partial y}\right] \tag{1}$$

$$\rho u \frac{\partial ho}{\partial x} + \rho v \frac{\partial ho}{\partial y} = \frac{\partial}{\partial y}\left[\frac{\mu}{Pr}\frac{\partial ho}{\partial y}\right] + \frac{\partial}{\partial y}\left[\mu\left(1-\frac{1}{Pr}\right)\frac{\partial}{\partial y}\left(\frac{u^2}{2}\right)\right]$$

$$+ \frac{\partial}{\partial y}\left[\rho D_{12}\left(1-\frac{1}{Le}\right)(h_A - h_m)\frac{\partial \alpha}{\partial y}\right] \tag{2}$$

where α is the atomic mass fraction, D_{12} the binary diffusion coefficient, and $h_A - h_m$ is the heat of dissociation. All other terms are defined by the standard flow notations.

Equations (1) and (2) are integrated and transformed into the equivalent incompressible forms. A set of governing equations required for the solution of real gas flow separation consists of the original Lees-Klineberg theory and the foregoing equations in the transformed form.

The real gas effects as defined under the present formulation, can occur only for the conditions in which $-0.7 \geq S_W \geq -1.0$. This is because the diffusion cycle of dissociation-recombination can only exist when the wall to stagnation enthalpy ratio is small. The extreme hypothetical condition occurs when the inviscid flowfield outside the boundary layer is fully dissociated ($\alpha_e = 1.0$) and the air near the wall is fully recombined ($\alpha_W = 0$). For this condition, Fay and Riddell[3] give the real gas transport properties as $Pr = 0.72$ and $Le = 1.4$. Therefore, the present real gas flow separation boundary-layer model is defined by $Pr = 0.72$, $Le = 1.4$, $\alpha_e = 1.0$, $\alpha_W = 0.0$, $S_W = -0.8$, $(h_A - h_m)/ho_e = 1.0$ where $S_W = ho_w/ho_e - 1$ is a total enthalpy function.

Boundary-Layer Profile Parameters

The accuracy of integral theory depends solely upon the quality of boundary/layer profile parameters. A set of laminar boundary-layer profile parameters have been generated using the modified Falkner-Skan-type equations, which include nonunity Prandtl number and atomic/molecular diffusion terms. The real gas profile parameters are restricted to the conditions specified in the foregoing section.

The real gas solutions which depict the shear function, enthalpy gradient, and atomic mass fraction distributions at wall vs the pressure gradient parameter β are shown in Fig. 1.

Presented as Paper 79-0212 at the 17th Aerospace Sciences Meeting, New Orleans, La., Jan. 15-17, 1979; submitted Jan. 29, 1979; synoptic received May 7, 1979. Full paper available from AIAA Library, 555 W. 57th St. New York, N.Y. 10019. Price: Microfiche, $2.00; hard copy, $5.00. **Order must be accompanied by remittance.**

Index categories: Supersonic and Hypersonic Flow; Jets, Wakes, and Viscid-Inviscid Flow Interactions; Computational Methods.

*Member of Technical Staff. Member AIAA.

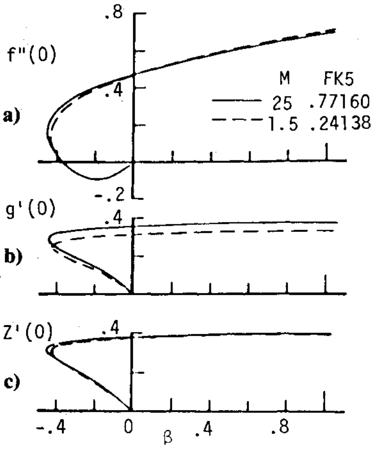

Fig. 1 Real gas laminar boundary-layer solutions: a) shear stress, b) total enthalpy gradient, and c) atomic mass fraction gradient at wall.

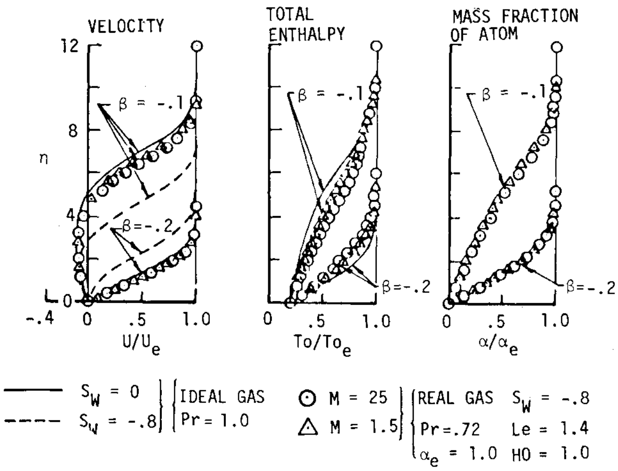

Fig. 2 Real gas laminar boundary-layer profiles for attached ($\beta = -0.2$) and separated ($\beta = -0.1$) flows.

The corresponding velocity, total enthalpy, and atomic mass fraction profiles for attached ($\beta = -0.2$) and separated ($\beta = -0.1$) flows are shown in Fig. 2.

Profile parameters that depend only on the velocity distributions are found to be independent of S_W when they are plotted against the boundary-layer form factor, $H_i = \theta_i/\delta_i^*$. These parameters are a universal function of H_i and are also applicable for the frozen real gas boundary layer. The wall shear parameters are highly dependent upon the parameter S_W.

The parameters which are a function of total enthalpy gradient at wall are generated for $Pr = 1.0$ and $Pr = 0.72$. Real gas flow with nonunity Prandtl number introduces a Mach number dependence in the energy equations, while a nonunity Lewis number introduces a coupling between the energy and the species equations. Therefore, these profile parameters showed a strong dependence on a quantity FK5 defined by Mach number and the ratio of specific heat. Although the quantity FK5 does not appear explicitly in the boundary-layer integral equations, the profile parameters include the effect of $Pr \neq 1$ and $Le \neq 1$ and, therefore, are properly accounted for in the analysis.

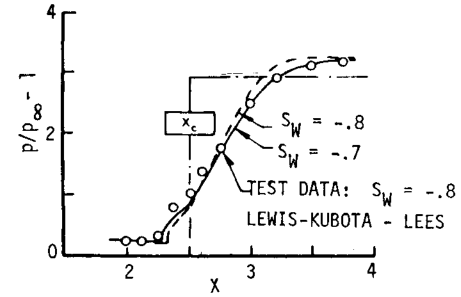

Fig. 3 Ideal gas pressure distribution comparison for Mach 6 flow: $\delta_e = 10.5$ deg, $Re_{x_c} = 1.5 \times 10^5$.

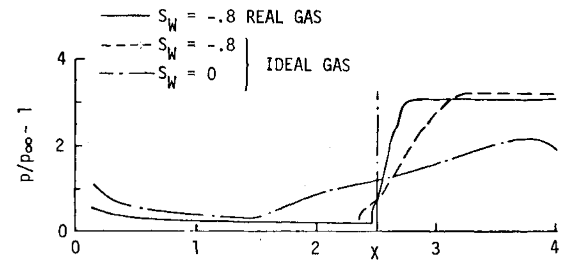

Fig. 4 Real/ideal gas pressure distribution comparison for Mach 6 flow: $\delta_e = 10.5$ deg, $Re_{x_c} = 1.5 \times 10^5$.

Results

The viscid-inviscid flow interaction prediction, based on the newly generated boundary-layer profile parameters, is checked against the experimental data of ideal hypersonic laminar flow separation. Pressure distributions for Mach 6 flow over a highly cooled wall compared favorably with the experimental data[4] (Fig. 3).

The predicted results of real/ideal gas viscous interaction for Mach 6 flow are shown in Fig. 4. The real gas solutions are compared for the same flow properties for direct data comparison. The atomic-molecular diffusion circuit within the boundary layer appears to produce higher flow separation impedance. The computations converge in 10-20 s CPU on an IBM 370. Wind tunnel simulation of the real gas flow phenomena discussed herein is extremely difficult to accomplish since very high enthalpy flow test conditions are required. In the author's opinion, no experimental data will be available for the analytical methodology substantiation until the flight of the SSO.

References

[1] Ikawa, H., "A Re-Entry Control Effectiveness Methodology for the Space Shuttle Orbiter," *Journal of Spacecraft and Rockets*, Vol. 14, Nov. 1977, pp. 669-675.

[2] Klineberg, J. M. and Lees, L., "Theory of Laminar Viscous-Inviscid Interactions in Supersonic Flow" *AIAA Journal*, Vol. 7, Dec. 1969, pp. 2211-2221.

[3] Fay, J. A. and Riddell, F. R., "Theory of Stagnation Point Heat Transfer in Dissociated Air," *Journal of the Aeronautical Sciences*, Vol. 25, Feb. 1958, pp. 73-85.

[4] Lewis, J., Kubota, T. and Lees, L., "Experimental Investigation of Supersonic Laminar, Two Dimensional Boundary Layer Separation in a Compression Corner With and Without Cooling," *AIAA Journal*, Vol. 6, Jan. 1966, pp. 7-13.