Base Flow Environment Analysis of a Single Engine Booster

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Theme

A METHOD of predicting the base pressure and the base gas temperature of an axially symmetric cylindrical vehicle with a single central jet has been developed with the application of Korst's two-stream interaction model. Reasonably good agreement of the analytical results with available wind tunnel and flight data has been obtained. Typical effects of geometry and of flow variables on base pressure and base gas temperature are also shown.

Contents

Some of the problem areas of major concern which exist during the powered phase of a launch vehicle are energy transfer from the engine exhaust gas to the base, possible recombustion of the fuel-rich turbine exhaust gas, and premature flow separation ahead of the base. The analysis of these problems requires a knowledge of base gas temperature, of ambient air entrainment into the base region, and of base pressure. The base flow of a booster depends on such variables as vehicle trajectory, hardware geometry, and engine operating conditions. Thus, a rather simple and practical method of predicting the base flow variables is desirable.

The usefulness of Korst's two-stream interaction model to the base flow analysis of an axially symmetric vehicle with a central jet (a typical vehicle shown in Fig. 1) has been demonstrated by several authors who obtained a good agreement of the predicted base pressure with data. In this paper the basic approach of Korst is extended to a more usable method which gives reasonably good prediction of not only the base pressure but also of the base gas temperature. The method is limited to a case where the mixing layer is fully turbulent and where both the external freestream and the central jet stream are supersonic. The initial boundary layer at the separation corner is neglected.

A mixing layer velocity profile of an error function shape with an expression for the jet spread factor based on some recent axisymmetric base flow data was used. Total enthalpy within the mixing layer was related to the velocity profile by Crocco's energy relation. The assumption that the recompression pressure rise equal to the pressure rise of the inviscid flow boundary across an oblique shock, together with Goethert's modified escape criterion, has been retained. It has been observed from recent data that the flow reversal begins well ahead of the rear stagnation point. The constant pressure mixing analysis is, therefore, applicable in the relatively constant pressure region between this beginning of flow reversal and the base.

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The inviscid flow boundaries of both the external and the central jets are first determined for a selected trial value of the base pressure and gas temperature. Using these boundaries as reference coordinates, one can determine the location and velocity of the jet boundary streamline from mass continuity and momentum considerations. The location and velocity of the reattaching streamline within the mixing layer are then determined from the magnitude of the recompression pressure rise and the escape criterion. The mass flow entrained into or out of the base region, and the energy carried by this flow are calculated by integrating the mass and energy fluxes between these two streamlines. The energy transferred across the jet boundary streamline over the distance between the base and any axial station is also calculated from the total enthalpy profile of the mixing layer. A unique base flow solution is obtained from mass and energy balance in the base region.

Although these analyses may be made at any axial station within the constant pressure base region, only the solution at the initial point of flow reversal is of interest. The amount of entrained mass continues to increase as constant pressure mixing takes place until the pressure rise initiates the flow reversal. Therefore, the amount of the entrained flow between the jet boundary streamline and the reattaching streamline is maximum at this point of flow reversal. The total amount of mass entrained into or out of the base region is then determined by this flow between the two streamlines. According to available base flow data on an axially symmetric blunt-based configuration, flow reversal appears to initiate at approximately one-half the distance between the base and the rear stagnation point.

The initial point of flow reversal for the case of two-stream interaction is not well understood. However, considering that the momentum flux of the central jet is generally much greater than that of the external stream, this point was assumed to be dictated by the central jet. The location of the external flow reversal point was, therefore, set along the inviscid flow boundary at a distance from the rear stagnation point equal to one half the separation length of the central jet. An alternate selection of the downstream boundary of the constant pressure region based on the half-way distance of the

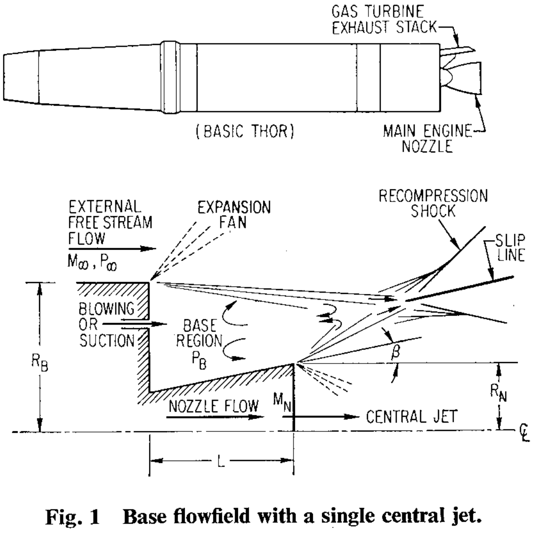

Fig. 1 Base flowfield with a single central jet.

separation length of each stream results in a rather unrealistic control volume shape as well as two pressure distributions not consistent with the constant pressure mixing analysis. The predicted base gas temperature tends to be higher (by about 100°F for the cases investigated) by this selection of the flow reversal location, whereas the predicted base pressure has been found insensitive to this change.

When mass is taken from the base region by either stream and escapes downstream, an average enthalpy of the base gas should be used in the energy computation unless both the external and the central jet streams as well as the bleed flow are identical. The enthalpy of the base gas used in this energy transfer calculation was represented by an averaged value weighted by the flow below the reattaching streamline of both streams and the base bleed. This averaging has been found to be important for an accurate prediction of the base gas temperature.

Typical comparisons of the predicted base pressure ratio P_B/P_∞ (base pressure/ambient freestream pressure) and base gas temperature with data are shown in Figs. 2 and 3. In the experimental data of Fig. 2, the nozzle extended length L relative to the base plane was zero, and cold air having the same total temperature as the tunnel stagnation temperature was used to simulate the exhaust jet. In Fig. 3, the model had an L of 64% of the base radius. The nozzle had an area ratio

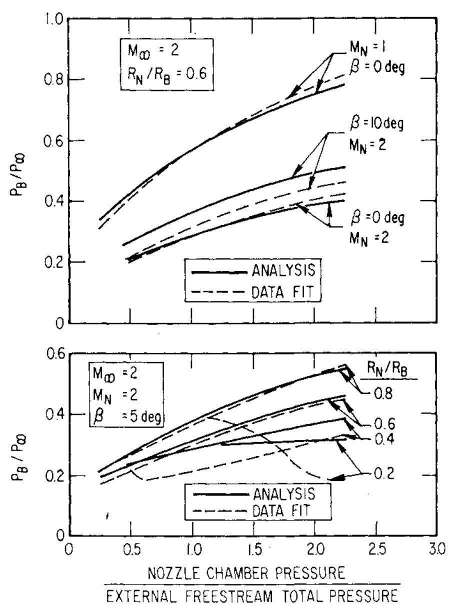

Fig. 2 Comparison of analysis with cold flow wind-tunnel data.

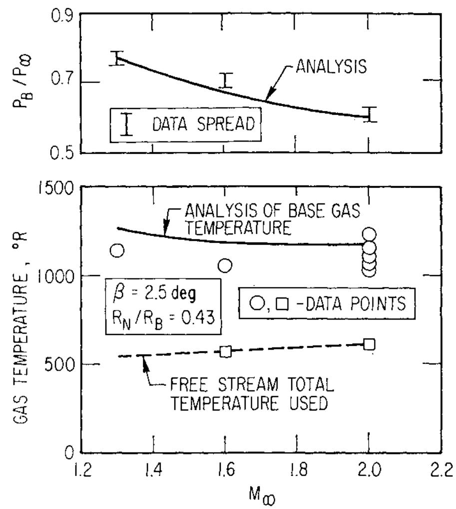

Fig. 3 Comparison of analysis with hot jet flow wind-tunnel data.

of 8. Both JP-4 and LOX were used as propellants. The method tends to over-predict the base pressure when the nozzle to base radius ratio R_N/R_B is small and when the nozzle exit angle β is large. A parametric study of the effect of flight Mach number M_∞, nozzle Mach number M_N, chamber and ambient conditions, nozzle geometry, and base bleed on base pressure and base gas temperature has been made and typical results are presented in the full paper. The predicted base pressure also agreed well with the flight data of the Thor booster.

In a recent work,[1] (not referenced in the paper), Addy presented a recompression model which was obtained by analyzing an extensive collection of available base pressure data consistent with the analytical method used. He found that the empirical recompression coefficient (reattaching streamline stagnation pressure/pressure downstream of the shock) could be correlated primarily with the nozzle to base radius ratio. Such a correlation would be a very useful tool and could improve the present base pressure prediction at small value of R_N/R_B. The effect of Addy's model on the accuracy of base gas temperature prediction has not been investigated.

Reference

[1] Addy, A. L., "Experimental-Theoretical Correlation of Supersonic Jet-on Base Pressure for Cylindrical Afterbodies," *Journal of Aircraft*, Vol. 7, No. 5, Sept.–Oct. 1970, pp. 474–477.