Analysis of Axially Symmetric External Burning Propulsion for Bluff-Base Bodies

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Abstract

EXTERNAL burning is presently visualized as a promising concept to be used for some flight missions which require or may benefit from substantial drag reduction or elimination during a portion of a supersonic trajectory. This concept was initially investigated by Strahle[1] for the two-dimensional case, and later by Smithey[2] for the axisymmetric case, both using the original Crocco and Lees[3] theory as the basic model. Recently, an axisymmetric base flow theory,[4] which is an extension of Alber and Lees'[5] two-dimensional work, was published and was shown to agree well with experiment. Here, a parametric study for an external burning propulsion system, using this recent theory as the basic model, was carried out to investigate potential performance of such a system. The external burning zone is incorporated in the inviscid portion of the aforementioned model. It is treated as a quasi-one-dimensional zone, and is considered both shear free and nonconducting. With these major assumptions, it is shown that it is possible to achieve very high base pressures using external burning. The specific impulse values obtained are lower than reported for the two-dimensional case. In many cases, the performance is less than usually achievable by conventional rocket propulsion, if current fuel-rich gas generators[6] provide the fuel for the external burning propulsion system. Recent experiments[7] carried out using compression surfaces to simulate external burning confirm the order of magnitude of the specific impulse obtained by this theory.

Contents

The type of external burning considered here is a concept that allows compression waves to impinge upon the near wake behind a bluff-base body and thereby to raise the base pressure. In order to gain a feel for the performance and to bring out the essential features of an external burning propulsion system, a simple model of an external burning zone is incorporated in the inviscid portion of a realistic near-wake axisymmetric turbulent base flow model as shown in Fig. 1. Fuel is considered fully dispersed in this zone, and there is no mixing across the bounding streamlines. The heat addition zone is displaced outward a sufficient amount so that heated streamlines do not intersect the viscous region before the wake closure singularity is encountered in the downstream numerical integration. This allows the near viscous wake to be treated under the restrictions of the parent model, i.e., adiabaticity, isoenergeticity, and an eddy viscosity model

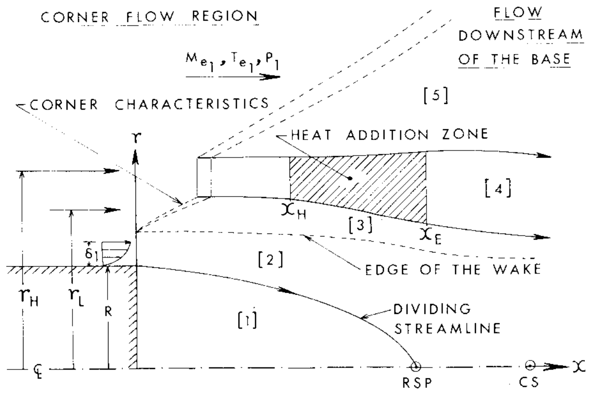

Fig. 1 Axisymmetric supersonic near-wake model with external burning. RSP = Rear stagnation point, CS = Crocco-Lees singular point.

given in Ref. 4. The parent model (without external burning) with the preceding assumptions was shown to give good results for Mach numbers M_{e_l} varying from 1.5 to 4, and for large variation of the upstream boundary-layer thickness δ_l, although these assumptions may be locally violated in the practical case.

The analysis follows the footsteps of the theory without external burning, and essentially consists of solving the corner flow region and the flow downstream of the base. The solution of the corner region provides the initial conditions for the downstream wake analysis. Assuming a 1/7th power profile for the initial boundary layer, a value of the base pressure, and an isentropic expansion in the outer streamlines, one can find the portion of the boundary layer below which the velocity gradient, $\partial u/\partial y$, after the corner expansion, is equal to or larger than that at the edge of the upstream boundary layer, $(\partial u/\partial y)_{\delta_l}$. This portion of the boundary layer is taken to start shear layer region 2.

The flow downstream of the base is divided into five regions. The inner regime, consisting of recirculatory region 1 and shear layer region 2, is represented by integrated boundary-layer equations, and the shear stress is modeled using an eddy viscosity model.[4] The outer portion of the boundary layer, in which shear stresses become very small after expansion, is considered inviscid but rotational after expansion. This portion and the portion of the flow between the boundary layer and the streamline distance r_L from the centerline form region 3, and are solved by an approximate rotational method of characteristics (MOC). In this way, any presence of fuel injection shocks can also be taken care of without modifying the program. Region 4 is formed by streamlines located radially r_L and r_H from the centerline, and is solved using one-dimensional gasdynamics, but with a centrifugal correction. The heat addition or burning takes place only in this region. x_H and x_E in the diagram indicate the start and the end of the heat addition zone. Region 5 is irrotational and inviscid, and treated with irrotational MOC. An iteration scheme is required to patch regions 3, 4, and 5.

The solution from the base is started using two-parameter Green's profiles.[8] The use of these profiles results in six

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unknowns in the problem, for an assumed value of the base pressure. The mass conservation equation, the momentum conservation equation, the mechanical energy equation, and the centerline momentum equation in conjunction with the simultaneous solution of the outer regime consisting of regions 3, 4, and 5 are used to solve for these unknowns. Away from the base, the velocity profiles are represented by the Kubota-Reeves-Buss[9] one-parameter profiles. As the number of unknowns is reduced by one using these profiles, the solution of three integrated equations and the outer regime is sufficient to calculate the five unknowns. The solution is continued downstream until the Crocco-Lees singularity is hit. If the initial value of base pressure guessed is low, the determinant of the solution matrix goes through zero before any of the numerators and vice versa. Thus, one can obtain the correct value of base pressure and the solution of the flowfield by iteration.

One-dimensional formulation of the external burning zone clearly points out the possibility of thermal choking taking place in this zone. One has to modify the program near this point to analytically take care of this singularity. The present computations are stopped before thermal choking occurs. Also, in the concept of pure external burning as used here, there is a high loss of energy because very hot gases leave the system.

The present calculations are made with a fuel of comparatively low calorific value, $H_f = 5556$ kcal/kg, as this value is achievable from current fuel-rich gas generators.[6] The freestream temperature T_{e_1} is assumed to be 288 K. The combustion is assumed to be 100% efficient. The maximum ratio of fuel to air that is permitted in the calculations is the stoichiometric fuel-air ratio.

Figure 2 shows the results of the computations carried out close to sonic conditions in the heat addition region with total temperature rise in the heat addition zone, $\Delta\bar{T}_o$, or fuel-air ratio $(= c_P\Delta\bar{T}_o/(H_f - c_P\Delta\bar{T}_o))$ as the parameter. These runs confirm the findings of previous research workers that high base pressure rise is possible using this concept. Also, this figure gives a feel for the specific impulse values that can be expected at practical base pressure rises with this method. The specific impulse decreases, i.e., the system becomes less efficient, both with the increase of the Mach number and increase of fuel-air ratio. The minimum value of the specific impulse, I_{sp}, shown in Fig. 2 is about 86 s occuring at Mach 3.0 with $\Delta\bar{T}_o/T_{o,\infty} = 2.27$, with a corresponding base pressure value equal to 1.85 times the ambient pressure. The maximum value of I_{sp} shown is about 198 s occurring at Mach 2.0 with $\Delta\bar{T}_o/T_{o,\infty} = 0.267$, with a corresponding base pressure value equal to 0.739 times the ambient pressure.

Next, a parametric study was conducted to delineate the importance of various design variables. It was found that the performance of an external burning system depends upon nine nondimensional parameters. This parametric study showed that the performance of an external burning propulsion system is strongly dependent only on the upstream Mach number, fuel-air ratio, the combustible mass, and the fuel calorific value. Also, the system becomes more efficient with a cold freestream. For preliminary design of this system, reasonable values of the heat distribution parameter, axial and radial locations, and length of the heat addition zone can be assumed, as their effect on the performance is only secondary. Thus, for a given base pressure rise, the optimization problem is reduced to the selection of r_H/R and $\Delta\bar{T}_o/T_{o,\infty}$. One rule of thumb which came out of these studies, and should be helpful in extrapolating experimental results, is that, except for very low heat additions, base pressure remains constant with Mach number and upstream boundary-layer thickness for the same values of other parameters.

The question whether the present values indicate an upper limit of performance is unanswered. To answer this question, one has to consider two effects, viz, the losses due to viscosity

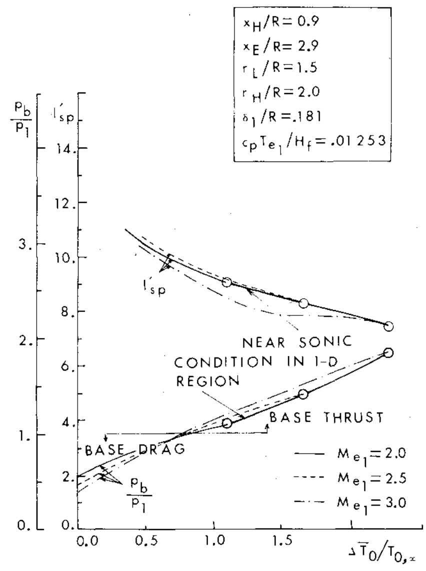

Fig. 2 High base pressure rise runs: specific impulse and base pressure vs total temperature rise in the heat addition zone. $I_{sp}' = I_{sp} M_{e_1} g_o / c_{e_1}$, nondimensional specific impulse parameter.

and the mass entrainment in the heat addition zone due to mixing. An improvement in modeling of the external burning zone is required to answer this question satisfactorily.

Finally, the present calculations show that, although high net thrust can be obtained using the external burning method, this method is not efficient unless a high calorific fuel is used. Its performance falls short of that of conventional rocket propulsion systems. However, it is still attractive because of the simplicity of design. Its performance probably can be boosted by combining this method with the base burning method, which is very efficient for low base pressure rise values. More experimental and theoretical work is warranted to check these conclusions.

Acknowledgment

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