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Incomplete Mixing and Off-Design Effects on Shock-Induced Combustion Ramjet Performance

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A shock-induced combustion ramjet ("shcramjet") model is described to investigate the effects of incomplete fuel/air mixing and off-design flight conditions on its performance characteristics. A fully implicit, fully coupled, Newton-iteration, lower–upper symmetric Gauss–Seidel scheme is employed to solve the Euler equations at steady state. This scheme is coupled with a nonequilibrium chemistry model consisting of 33 reactions and 13 species. Axisymmetric and planar shcramjet flowfields with variable equivalence ratio profiles representing extreme deviations from homogeneous fuel/air mixing are numerically solved for a range of flight Mach numbers at a constant dynamic pressure of 1400 psf. Results show that incomplete fuel/air mixing gives rise to a combination of detonative combustion and simple shock-induced combustion. Comparison of overall performance characteristics to shcramjets with homogeneous, stoichiometric fuel/air mixtures demonstrates the degree of performance degradation. The propulsive characteristics of mixed-compression ramjets are calculated in off-design operating regimes corresponding to inlet Mach numbers above and below design Mach numbers of 12, 16, and 20; for external-compression ramjets, the propulsive characteristics are calculated for inlet Mach numbers below design Mach numbers of 12, 16, and 20. It is found that the propulsive properties of the engines deteriorate when they are operated at off-design conditions. For mixed-compression ramjets operating at lower-than-design Mach numbers, the degradation in thrust production is due primarily to reduced heat release in the engine nozzle. At higher-than-design Mach numbers, thrust production is reduced only slightly due to a modified nozzle geometry, required to ensure convergence of the numerical method. Generation of thrust for external-compression ramjets deteriorates at lower-than-design Mach numbers due to a high-pressure zone created in the combustor by the impingement of the detonation wave on the engine surface upstream of the design point. Mixed-compression ramjets are found to provide superior performance to external-compression ramjets at off-design operation. External-compression ramjets are found to be more sensitive to off-design operation than mixed-compression ramjets. It is concluded that the engine geometry must be varied as flight conditions change if degradation in engine performance at off-design conditions is to be avoided.

Introduction

A GROWING area of interest in hypersonic propulsion is the shock-induced combustion ramjet, or "shcramjet." In this mode of heat addition to the supersonic flow, the fuel/air mixing process is decoupled from the combustion process. The mixing is organized in the vehicle forebody, which also serves as the inlet of the engine. Combustion in the more or less homogeneous fuel/air mixture is then achieved by a conveniently located shock wave that raises its temperature and pressure to its ignition point. It is clear that homogeneously mixing the streamwise-injected fuel with the hypervelocity forebody/inlet shock-layer flow prior to combustion is a technically challenging task. However, the mixing problem may be mitigated by the relatively long residence time the fuel will have in the propulsive airstream contained by the long and slender forebody of the vehicle. Other practical issues must also be resolved to achieve satisfactory operation of shcramjets.[1] In this earlier investigation, the aeropropulsive performance parameters of shcramjets were derived from the numerical simulation of the entire hypersonic flowfield around a specific planar or axisymmetric shock-induced combustion ramjet model. A baseline study of external- and mixed-compression on-design shcramjets has been carried out (Fig. 1) where the tangentially injected fuel in the forebody flow was assumed to be homogeneously mixed with the incoming air. Results obtained showed that shock-induced combustion can be used as a viable means of hypersonic propulsion.

Despite these encouraging research efforts concerning shcramjets, there are many aspects that require further investigation to allow the concept to come to fruition. This paper contains the results of two studies concerning the impact 1) of nonuniform fuel/air mixing effects arising from practical difficulties of fuel injection into a hypersonic flow; and 2) of off-design, i.e., an engine operating under flight conditions for which it was not designed, on the propulsive performance of shcramjets. The design of a shcramjet engine is inextricably linked to the flight conditions under which the engine is to operate to the extent that, ideally, the engine geometry will vary with varying flight conditions. Because it would be practically difficult for the engine's geometry to vary continuously along the flight path, the geometry would likely remain fixed over discrete flight Mach number intervals within which performance does not deteriorate too significantly. Extreme degradation of performance may mean that, in its present form, the shcramjet engine is not practically viable. Minor degradation can indicate that shcramjet propulsion is elastic with respect to operating conditions, and that the degradation in performance may be overcome by minor modifications to the engine design or may be small enough to warrant no change.

To date, only a few studies on the extent to which nonuniform fuel/air mixing and off-design flight conditions affect shcramjet performance have been presented in the published literature. Cambier et al.[2] investigated the effects of nonuniform fuel/air mixing on the structure of a detonation wave. Their study employed a two-dimensional Navier–Stokes code to compare the flow of a

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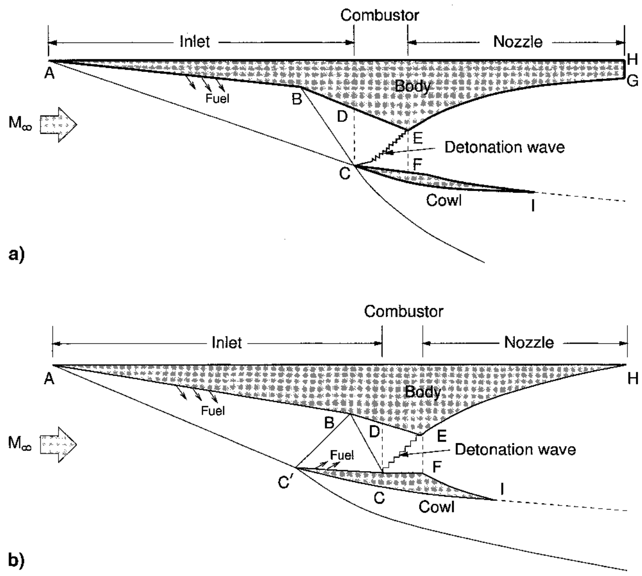

Fig. 1 Schematic shcramjet configurations: a) external and b) mixed compression.

hydrogen/air mixture over a wedge having uniform stoichiometric mixing with a flow having a pseudosinusoidal function of equivalence ratio in the range $0.1 < \phi < 1.9$. It was shown that a flow with variable equivalence ratio produced a more complex curved detonation front in which the flame is strongly coupled to the wave front. The study found that the structure of the detonation wave is dominated by mixing properties such as variation in molecular weight and Mach number, rather than heat-release fluctuations. This situation is referred to as a "mixing-controlled environment." It was concluded that the shock-induced combustion concept can be extended to such an environment. The study was limited to the investigation of effects on the detonation wave itself without an analysis of a complete shcramjet configuration.

Morrison[3] published a report in which off-design shcramjet performance was considered as part of a larger assessment of shcramjets for hypersonic air-breathing propulsion. His analysis was based on a mixed- and an external-compression shcramjet designed for operation at Mach 8, and used an ideal-gas model with a constant specific heat ratio and simple heat addition (solution of the Rankine–Hugoniot equations) for the detonation wave. Both shcramjets were designed with the intention of minimizing both spillover at Mach numbers below the design Mach number and shock ingestion at Mach numbers above the design Mach number, while keeping the diffuser length from becoming excessive. The results of his study showed that both types of shcramjet suffered performance degradation at off-design conditions. He found that the external-compression shcramjet offered the most compact design and efficient performance at on-design operation, whereas the mixed-compression shcramjet, although not as compact as the external-compression shcramjet, was nearly as efficient at the design point and also provided good performance for a range of off-design flight Mach numbers. For the external-compression shcramjet, large spillage losses occur at lower-than-design Mach numbers, whereas at high Mach numbers, the intake shocks intersect within the ingested airstream leading to the formation of a third shock, incurring high-stagnation pressure losses. With this type of shcramjet, stagnation pressure losses were found to be greater at higher-than-design Mach numbers than at lower-than-design Mach numbers, whereas degradation of thrust coefficients and specific impulses were smaller at higher-than-design Mach numbers than at lower-than-design Mach numbers. The study showed that the mixed-compression shcramjet experienced less spillover at lower-than-design Mach numbers than the external-compression shcramjet, and also that the absence of shock intersections in the mixed-compression shcramjet reduced the losses at higher-than-design Mach numbers. In general, the performance of the mixed-compression shcramjet always exceeded that of the external-compression shcramjet at off-design operating conditions. On the basis of these findings, Morrison[3] concluded that the mixed-compression shcramjet offers the least complex geometric configuration amenable to off-design operation.

Ostrander et al.[4] developed a computer code to assess the performance of a mixed-compression shcramjet using an ideal-gas model with constant but different specific heats upstream and downstream of the detonation wave. The gas in the engine was assumed to be broken up into four distinct zones: one of pure air (N_2, O_2, and Ar) in the inlet, followed by pure H_2 in the injection region, and perfectly mixed air and H_2 before the detonation wave; after the detonation wave, complete, frozen combustion products were assumed. Their code did not solve the chemical kinetic equations for the combustion of hydrogen in air, but used an empirical formula to estimate the induction time, and hence, the induction distance for the hydrogen/air reactions; if the induction distance was found to be less than 1 ft, a detonation was deemed to have formed. The postdetonation state of the gas was determined from the oblique shock equations plus the energy equation with an additional heat-release term. The products of combustion were considered frozen in composition during expansion in the nozzle. The engine geometry was generated by the code based on a specified forebody angle and cowl height and the constraint that the first two intake shocks be of equal strength. The remaining geometric parameters were varied until the induction distance was found to be less than 1 ft. The off-design performance data generated by their computer code predicted better performance of the engine in terms of fuel-specific impulse and thrust per unit area for off-design operation than for operation at design conditions. A source of error that may account for this questionable result is the method by which the shock intersection at higher-than-designMach numbers was treated. Instead of solving the actual shock intersection, the authors averaged the flowfield properties and used these as upstream conditions for a standard detonation-wave solution. The authors themselves expressed doubt as to whether it is possible to assess the inaccuracies associated with this approach without actually solving the detonation-shock interaction. Furthermore, with their formulation, it is not clear whether a detonation wave can be established or will extend all the way across the flowfield at off-design conditions.

Most recently, Atamanchuk and Sislian[5] carried out a comprehensive study of off-design shcramjet performance. They used a first-order Godunov numerical method with a perfect gas model, simple heat addition, and constant specific heats to determine the off-design performance of mixed- and external-compression shcramjets. By specifying the forebody deflection angles, the freestream conditions, and the flight Mach number, the inlet geometry was determined. The remaining on-design characteristics were determined by specifying the cycle temperature ratio T_{max}/T_∞ and the amount of heat addition for the detonation wave; i.e., whether it is a Chapman–Jouguet (CJ) or an overcompressed detonation. In this study, the off-design analysis was then carried out by varying the amount of heat addition Q required to maintain cruising conditions (a thrust-to-drag ratio of 1). As expected, the results of the simulation showed that off-design performance of the shcramjet was always inferior to performance at design conditions in terms of propulsive efficiency. On the basis of the results of their numerical simulation, Atamanchuk and Sislian concluded that the mixed-compression shcramjets could operate over a wider range of the off-design flight Mach numbers than the external-compression shcramjets. The three studies reviewed are the only investigations into off-design shcramjet performance to be found in the published literature. While each study has made useful contributions to the field of shcramjet technology, each has its own limitations and deficiencies.

Morrison's study,[3] the first to offer any sort of assessment of off-design shcramjet performance, was based on a simple ideal-gas model with constant specific heats and to completely disregard the hydrogen/air chemistry of the shock-induced combustion. Ostrander et al.[4] also employed an ideal-gas model, but modeled the hydrogen combustion with empirical formulas. However, the applicability of the modeling approach they used and the validity of their results is questionable considering that they obtained better performance for the engine during off-design operation than during on-design operation. Also, their design procedure did not necessarily produce an engine geometry that minimized losses or maximized performance. The work of Atamanchuk and Sislian[5] was the first to employ a two-dimensional numerical simulation in the investigation of off-design shcramjet performance. However, the detonation wave was modeled by simple heat addition, meaning that again the hydrogen/air reaction was not taken into consideration. In fact, the amount of heat addition was varied independently of the flight Mach number. Because, in reality, the amount of heat released depends on the strength of the detonation wave, and hence, on the flight Mach number, this aspect of the study was clearly not realistic. Also, the Godunov numerical method used was only spatially first-order accurate, a definite limitation when a more detailed analysis needs to be carried out. Finally, the engine geometry was not designed to provide CJ or near-CJ detonation.

A model for a shcramjet that addresses the deficiencies of, and is more physically realistic than, the previous three studies is thus required for a more accurate investigation into off-design shcramjet performance. Also, at the present time, there have been no investigations on the effect of incomplete fuel/air mixing on the performance characteristics of shcramjets. This paper addresses these important issues.

Shcramjet Design Methodology

The two main types of shcramjet configurations considered in this paper are shown in Fig. 1. The design methodology behind each component of the engine—inlet, combustor, and nozzle—is geared toward minimizing entropy production in each component and is described in detail in Dudebout et al.[1] The shcramjet design methodology is given here briefly for completeness and includes modifications dictated by the present study.

Inlet

External Compression

The flow passes through two shocks in the inlet (AC and BC) (Fig. 1), which raise the temperature and pressure of the fuel/air mixture. The inlet is designed to ensure that the static temperature after the second inlet shock remains below the spontaneous ignition temperature of the mixture (assumed to be 900 K) to avoid uncontrolled and deleterious burning. The geometry of the inlet is designed to provide equal strength shocks to minimize entropy production.[6] For on-design considerations, the position of the cowl tip is specified at the intersection of the two inlet shocks. The overall length of the inlet is scaled to be 15 m, which is considered to be the characteristic length of the shcramjet. Fuel (hydrogen) is injected into the flow in the inlet and mixed with oncoming air before it reaches the combustor. In the case of the on-design baseline configuration, the fuel and air are assumed to be homogeneously mixed at an equivalence ratio of unity on entry to the combustor. This is simulated by specifying such a mixture as an inflow condition for the portion of the flow between the body and cowl tip. Consideration of nonuniform fuel/air mixing is simulated with a Gaussian distribution of equivalence ratio ϕ, as an inflow condition (Fig. 2):

$$\phi = Ae^{-By^2} \tag{1}$$

It is well known[7] that a Gaussian distribution is used to describe the near-field fuel concentration profiles in a round jet issuing into the surrounding atmosphere. It is assumed here that in the early stages of mixing of an injected fuel, e.g., from an inlet wall slot, with oncoming air, the fuel concentration profile will be similar to the single-jet near-field concentration distribution, and that it persists (no further mixing occurs) as the flow proceeds through the inlet up to the combustion zone. Therefore, the assumed Gaussian distribution of the equivalence ratio represents the worst fuel/air mixing case, and propulsive characteristics obtained in this case will represent their extreme degradation (lower limiting values). The constants in the Gaussian distribution are determined from the following conditions: the maximum value of ϕ occurs at $y = 0$; the total integrated

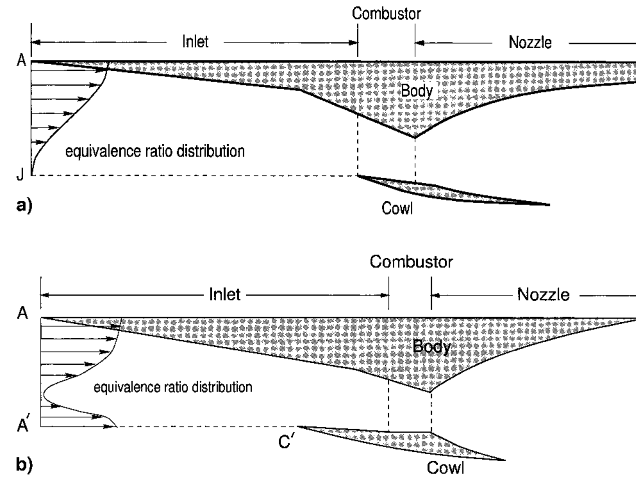

Fig. 2 Equivalence ratio profile schematic: a) external and b) mixed compression.

fuel mass flux is equal to a uniform stoichiometric distribution (homogeneously mixed case) over the capture area of the inlet section between the tips of the body and the cowl, AJ (Fig. 2a), taken equal to 3σ, where σ is the standard deviation. The result is a distribution that ranges from $\phi \approx 2.4$ at the body to $\phi \approx 0.02$ at the farthest point from the body. However, the position of the tip of the cowl is not known a priori. An iterative procedure is employed to distribute the equivalence ratio profile over the proper spatial range.

Mixed Compression

The resulting shock system is composed of three equal strength shocks (AC′, BC′, and BC), as shown in Fig. 1b. Specification of the hydrogen/air mixture temperature and distribution are identical to those of the external-compression shcramjet. The tip of the cowl is positioned to intersect the shock AC′ for on-design operation, and the characteristic length of 15 m is taken to be the axial component of AC′. Unlike the external-compression shcramjets, the mixed-compression shcramjet design uses both the inlet body and cowl as regions of fuel injection (see Fig. 1b). This provides high concentrations of fuel near both walls, with decreasing amounts as the distance normal from either fuel injector increases. As in the case of external compression, the fuel distribution from each of the injectors is modeled after a Gaussian curve. Because the fuel has two injector sources, a summation of two Gaussian curves is used. The maxima of the curves are at the boundaries of the flow, $y = 0$ and $y = \mathrm{AA}' = L$ (Fig. 2b), therefore,

$$\phi = Ae^{-By^2} + Ce^{-D(y-L)^2} \tag{2}$$

The four constants in this distribution are determined from the following requirements (assumptions):

1) The first requirement is to have equal maximum fuel-equivalence ratios at each boundary. Because of the geometry of the mixed-compression shcramjet, the body inlet wall is about three times longer than the cowl inlet wall (Fig. 2b). Therefore, the fuel injected from the body side will stretch farther into the flow with a longer time available for it to diffuse compared with the cowl side.

2) It is then assumed that the minimum equivalence ratio ($\phi \approx 0$) will occur at two-thirds of the full breadth of the inlet L.

3) Following this reasoning, the assumption is made that roughly two-thirds of the total fuel is contained between the body inlet wall and this minimum point.

4) Finally, the resulting distribution is scaled to produce a curve with an average equivalence ratio equal to unity (the same as in the homogeneously mixed baseline case). This distribution resulted in a curve that ranged from $\phi \approx 3.5$ at either wall boundary to $\phi \approx 0.02$ at the minimum, a length $\frac{2}{3}L$ from the body wall (see Fig. 2b).

Combustor

Flow from the inlet is ignited in the combustor via a shock generated by the combustor wedge (line CF). This oblique shock raises the temperature of the fuel/air mixture above its ignition point, and combustion ensues. If the chemical reactions involved in the combustion are very rapid and couple with the final shock (CE), a detonation wave is formed. For equilibrium flows with heat addition, classical gasdynamic theory predicts the existence of a detonation wave for which entropy production, and hence stagnation pressure losses, are a minimum. Such a detonation wave is known as a CJ detonation. Dudebout et al.[1] has shown that a CJ condition also occurs for nonequilibrium flows. The combustor angle is chosen to achieve a minimum of entropy production while maintaining stability. Thus, a CJ angle plus 3 deg (overdriven) is prescribed for on-design configurations. The overdriven case has the advantage of reducing the induction distance (and hence, the combustor length), with only a slight increase in entropy over the CJ angle. However, in the case of nonuniform fuel/air mixing, the structure of the detonation wave is not comparable with that of the preceding reference, and thus, the condition of minimum entropy through the detonation wave is not applicable as a design criteria in choosing the appropriate cowl wedge angle. The design criterion used in the nonuniform fuel/air mixing case is maximum overall net thrust. This criterion is based on the assumption that maximization of thrust implies a minimization in entropy production, and thus, the results of the shcramjet flowfield analysis can be compared with those presented in Dudebout et al.[1] Using the numerical solution for the inlet and combustor sections and employing the method of characteristics for calculating the nozzle flow (see next section), the overall net thrust of the shcramjet can be determined. Estimation of net thrust in this manner was subsequently shown to have excellent overall agreement with results obtained from the employed Euler numerical solution of the integrated shcramjet flowfield. The cowl wedge angle used in the design of the combustor is that which produces the greatest overall thrust. A plot of thrust as a function of cowl wedge angle (line CF) is shown in Fig. 3 for the external-compression axisymmetric shcramjet, $M_\infty = 14$ case. It can be seen that a distinct maximum thrust exists over the range of wedge angles solved (in this case at $\delta = 6$ deg). The cowl angle corresponding to the maximum thrust is determined for each configuration and case independently.

The investigation into off-design shcramjet performance ideally should be carried out by varying the flight conditions for fixed engine geometries. Some practical considerations prevent this for higher-than-design Mach numbers. At flight Mach numbers higher than the design Mach number, the shock angles, including the detonation-wave angle, become more shallow. As a result, the detonation wave no longer impinges on the combustor wall, but is ingested by the nozzle. With the detonation wave downstream of the nozzle "throat" (EF section in Fig. 1), the low-energy flow along the combustor wall upstream of the nozzle throat must turn the sharp corner situated at point E. In this case, the iterative lower–upper symmetric Gauss–Seidel (LUSGS) numerical scheme employed in the present study produces nonphysical (negative) temperatures at the corner.

To prevent this from happening, some modifications to the combustor geometry have been made for the cases where the flight Mach number is greater than the design Mach number. The combustor surface on the body side of the engine is redesigned (lengthened) according to the procedure outlined in the preceding text, so that the detonation wave can no longer extend into the nozzle. Point F, the nozzle throat on the cowl side of the engine, remains unchanged. The nozzle is redesigned using the new slanted line EF as the initial value line for the method of characteristics. Although redesigning the nozzle results in further changes to the engine geometry, it is necessary if shocks in the nozzle are to be avoided. For the cases where the flight Mach number is less than or equal to the design Mach number, the flow just upstream of the nozzle throat is at post-detonation conditions, and sufficient heat has been added so that this temperature drop poses no problems.

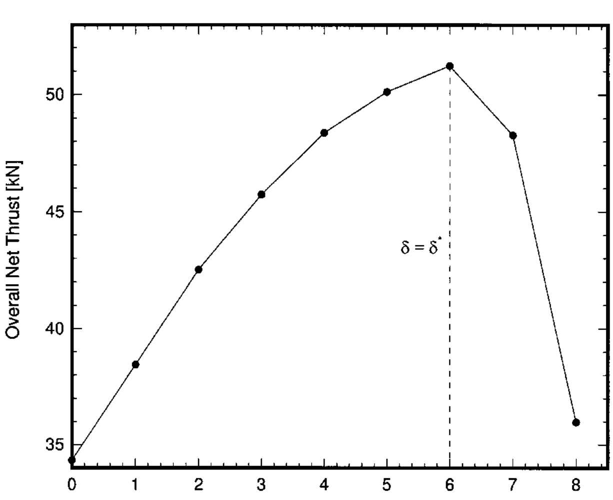

Fig. 3 Thrust as a function of cowl angle (line CF in Fig. 1) for an axisymmetric shcramjet, $M_\infty = 14$ case.

Nozzle

The design goal of the shcramjet nozzle is to specify the wall contours that expand the flow such that internal shocks are avoided and losses are therefore minimized. Because of the curved shock-detonation wave presented in the combustor, the method of characteristics for rotational flow was employed to specify the nozzle contours. The design criteria for the nozzle in the present study is that the flow be expanded to a specified static pressure P_e and be parallel to the shcramjet axis (which is parallel to the freestream flow), at the exit plane. The nozzle exit pressure is chosen so that the flow is expanded to the shcramjet axis. The flow is assumed to be frozen at the combustor outflow. A false-wall technique was used for external-compression configurations, whereas the dual-wall design was used for mixed-compression shcramjet models. Substantial savings in nozzle length with corresponding minimal thrust losses are attainable through nozzle truncation. The nozzle in the present study has been truncated so that only 5% of component thrust is lost. The savings in length would result in reduced drag due to frictional shear forces. Having specified the nozzle contours as outlined earlier, the entire shcramjet flowfield is solved using the Euler equations. Good agreement has been found between the method of characteristics (MOC) solution and the nonequilibrium chemistry (Euler) solution, lending credibility to the assumption of frozen flow in the nozzle section.

Governing Equations and Numerical Simulation

The planar or axisymmetric shcramjet flowfield is described by the Euler equations for a reacting, multispecies gas in chemical nonequilibrium in curvilinear coordinates and conservative form.[1] The hydrogen/air combustion chemistry model employed was suggested by Jachimowsky.[8] It consists of 33 reactions between 13 species (H_2, O_2, H, O, OH, H_2O, HO_2, H_2O_2, N, NO, HNO, N_2, and NO_2). The numerical method employed is a fully implicit, fully coupled, Newton-iteration, total variation diminishing (TVD) scheme for solving nonequilibrium, chemically reacting flows at steady state. It combines the LUSGS method developed by Yoon and Jameson[9] and a TVD scheme developed by Yee.[10] The numerical scheme used has been validated by comparison with analytical results where available, and experimental exothermic blunt-body flows investigated by Lehr.[11]

Results and Discussion

Incomplete Fuel/Air Mixing Effects

The combustor flowfields resulting from the variable equivalence ratio distributions depicted in Fig. 2 are shown in Figs. 4a and 4b.

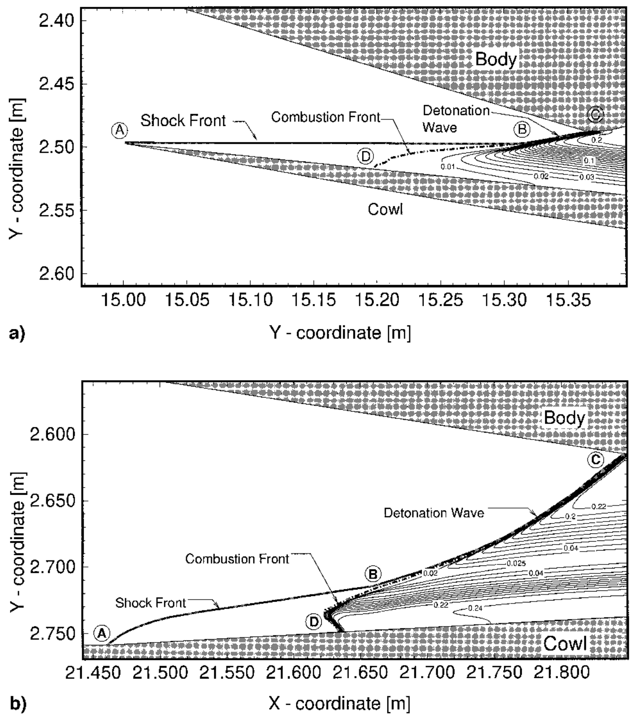

Fig. 4 Shock-induced combustion-detonation wave configurations generated by nonuniform fuel/air distributions and H_2O mass-fraction contours: a) axisymmetric external-compression shcramjet, $M_\infty = 14$, $q_{dyn} = 1400$ lb/ft^2 and b) planar mixed-compression shcramjet, $M_\infty = 10.4$, $q_{dyn} = 1400$ lb/ft^2.

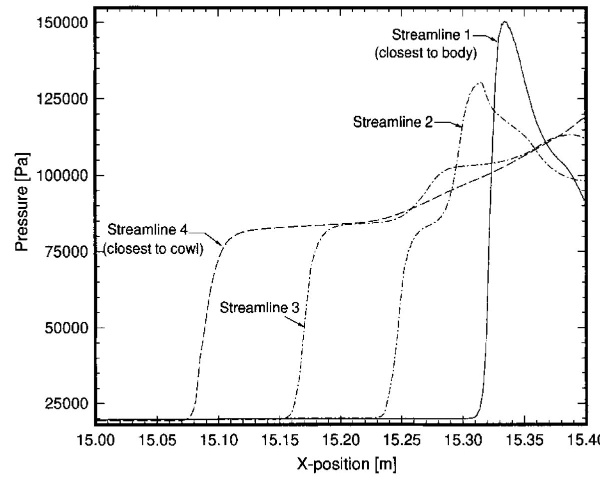

Fig. 5 Pressure distribution along streamlines in the combustor of an axisymmetric external-compression shcramjet at $M_\infty = 14$, $q_{dyn} = 1400$ psf.

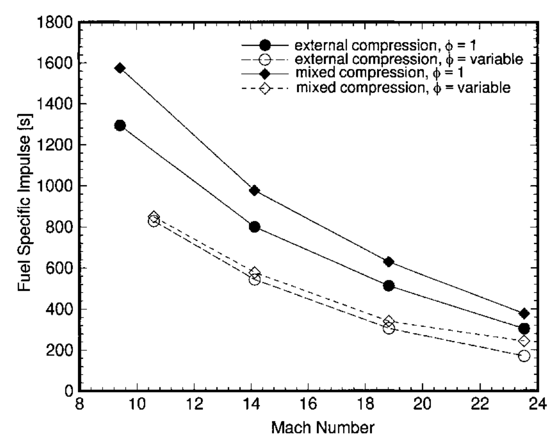

Fig. 6 Fuel specific impulse as a function of flight Mach number for planar shcramjet configurations, $q_{dyn} = 1400$ psf.

In contrast to the ideal case of stoichiometric, uniform fuel/air distribution considered in Dudebout et al.,[1] where the combustor flow consisted mainly of a near CJ detonation wave with a very short shock-induced combustion region, the effect of the extreme fuel/air mixing nonuniformity considered here is to significantly increase the ignition delay distance in both external- and mixed-compression shcramjets. The ignition delay distance AD are 25 and 18 cm, respectively, as compared with 5 and 3 cm for the uniform fuel/air distribution case at the same design and flight conditions. Coupling of the combustion and shock fronts occur between points B and C, and there is appreciable curvature of the wave front. As a consequence, the combustor will be larger than those that consist almost exclusively of a detonation front (uniform mixing) due to the steeper angle associated with this front. This length increase due to nonuniform fuel/air mixing will cause performance degradation in the form of increased drag and cooling loads for the combustor section. Indicative of combustion activity behind the wave front are the water mass fraction contours shown in Figs. 4a and 4b. (The combustion front is defined as the locus of points where the H_2O mass fraction is 1% of its maximum value.) Pressure variations along four streamlines in the combustor for an axisymmetric external compression shcramjet at $M_\infty = 14$ (corresponding to Fig. 4a) are shown in Fig. 5 (streamlines 2 and 3 are equally spaced between streamlines 1 and 4). It can be seen that after an initial rise through the wave front along streamlines 1 and 2, the flow is almost immediately expanding. Therefore, the combustor flow is more indicative of a post-CJ detonation flowfield. Figure 6 shows the net fuel specific impulse for planar shcramjet configurations over the Mach number range 8–24. Comparison of the incomplete fuel/air mixing case (ϕ variable) with the curve representing a shcramjet with a homogeneous stoichiometric ($\phi = 1$) fuel/air mixture, shows a degradation in performance over the Mach number range considered. A decrease of approximately 29 and 44% in fuel specific impulse is shown in Fig. 6 for the lower and upper limits, respectively, of the flight Mach number range considered. The mixed-compression, incomplete mixing case shows a loss in fuel specific impulse of 40% at the lower bound and 33% at the upper bound. This decrease over the flight Mach number range considered shows more degradation in the specific impulse due to incomplete fuel/air mixing than the external-compression case. Comparing these data with the typical value of a rocket (400s) suggests that, even with the loss in impulse due to incomplete mixing, the mixed-compression design shows superiority up to nearly the Mach 22 point.

Off-Design Flight Effects

The flowfield in the combustor changes considerably during off-design operation. The key features are shown in Figs. 7–10 by considering a planar mixed-compression shcramjet with a uniform fuel/air distribution designed for Mach 16, operating at off-design flight Mach numbers of 15 and 17 (slightly below and above the design Mach number). Because the third shock from the inlet, at flight Mach number 15, impinges on the cowl surface upstream of the leading edge of the detonation wedge, a reflected shock is formed at the point of impingement and intersects the shock formed at the leading edge of the detonation wedge. Temperature contours in this complex wave-interaction region are shown in Fig. 7. At this lower-than-design Mach number, the detonation-wave angle is higher than at the on-design Mach number, causing the wave to impinge on the body surface upstream of the nozzle inlet, shown in detail in Fig. 8. Because of the converging cross section of the combustor, a reflected shock begins to form between the point where the detonation wave hits the body surface and the nozzle inlet. Once the flow reaches the nozzle inlet, however, rapid expansion takes place, causing the reflected shock to die out. This high-temperature, high-pressure region is one of the causes of the degradation of the engine's performance

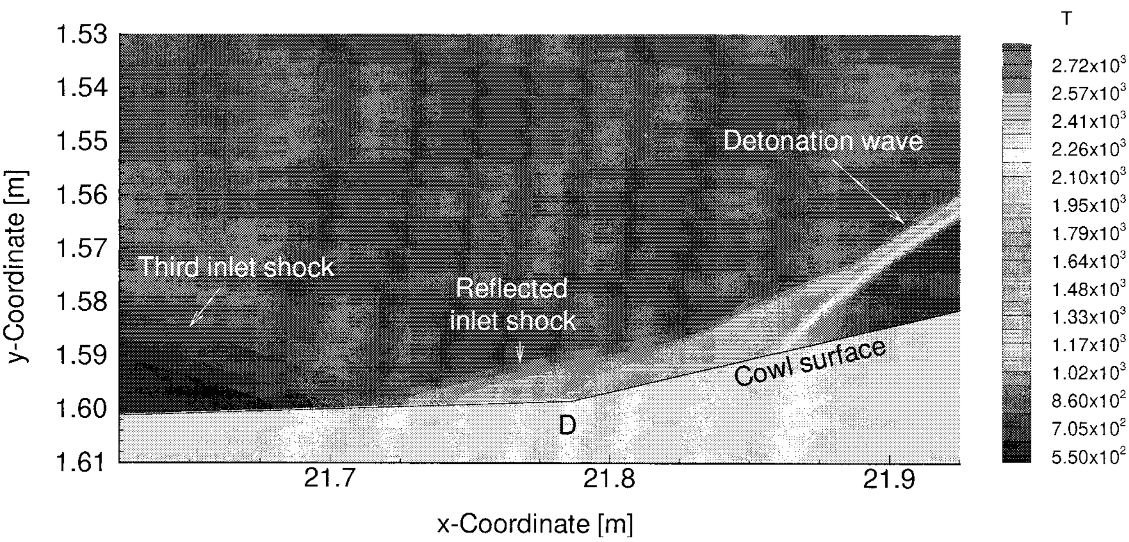

Fig. 7 Temperature contours near leading edge of detonation wedge in mixed-compression shcramjet combustor for Mach 15 (off-design) operation.

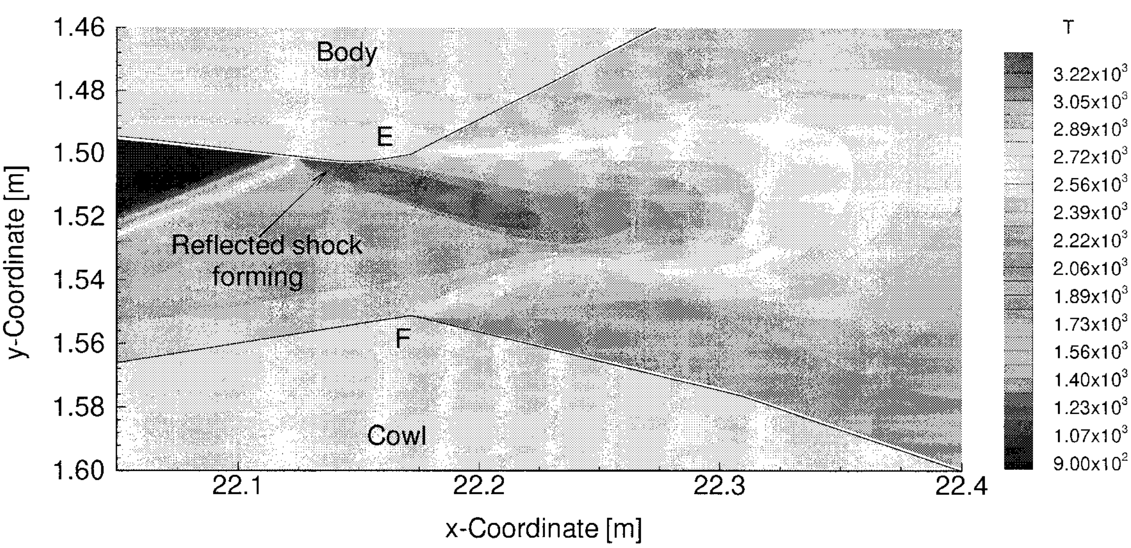

Fig. 8 Temperature contours near nozzle throat in mixed-compression shcramjet combustor and nozzle for Mach 15 (off-design) operation.

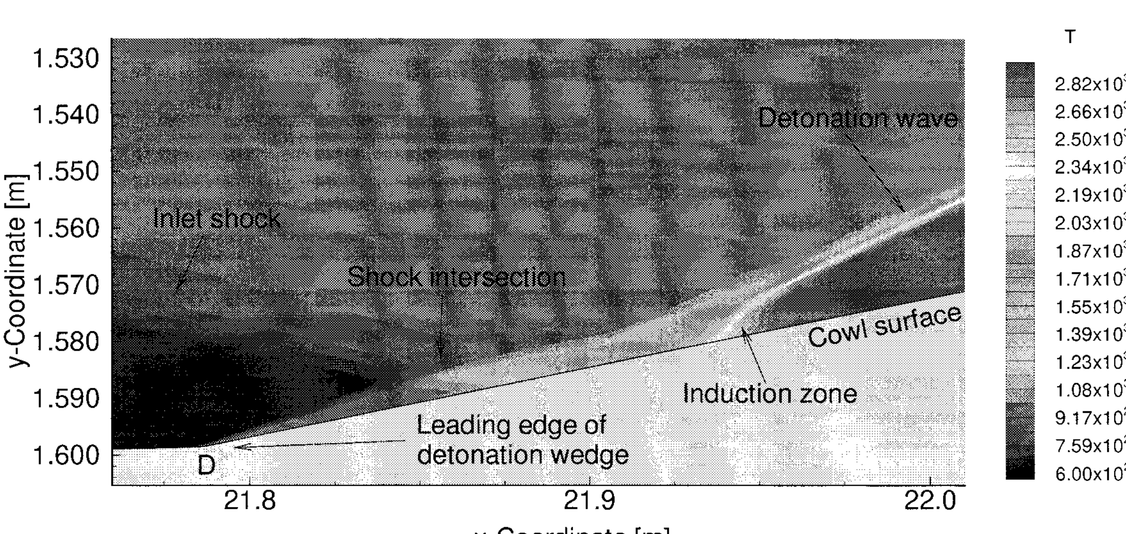

Fig. 9 Temperature contours in induction zone region for Mach 17 (off-design) operation of mixed-compression shcramjet.

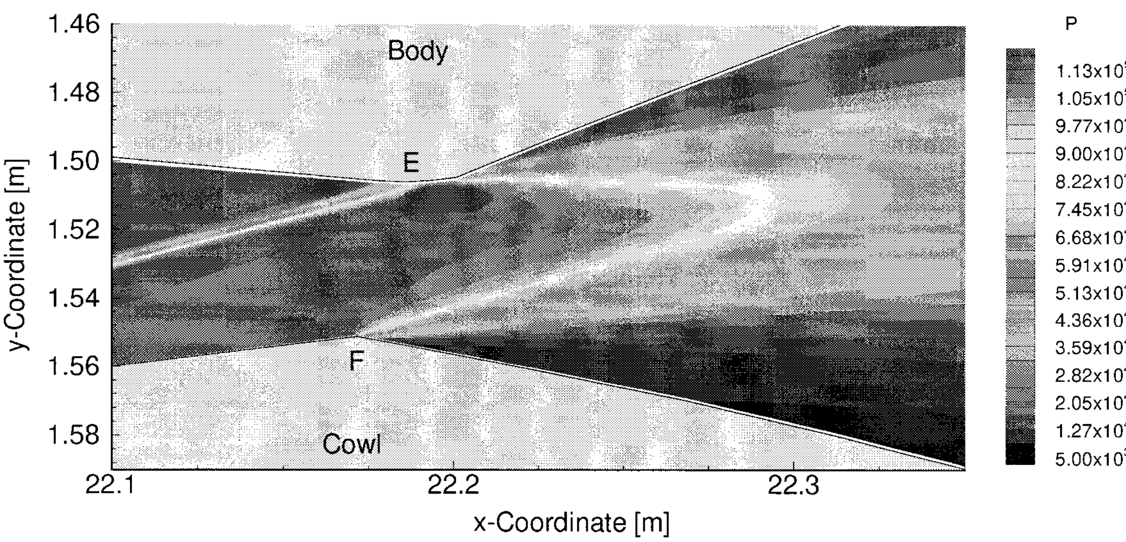

Fig. 10 Pressure contours at nozzle throat in mixed-compression shcramjet for Mach 17 (off-design) operation.

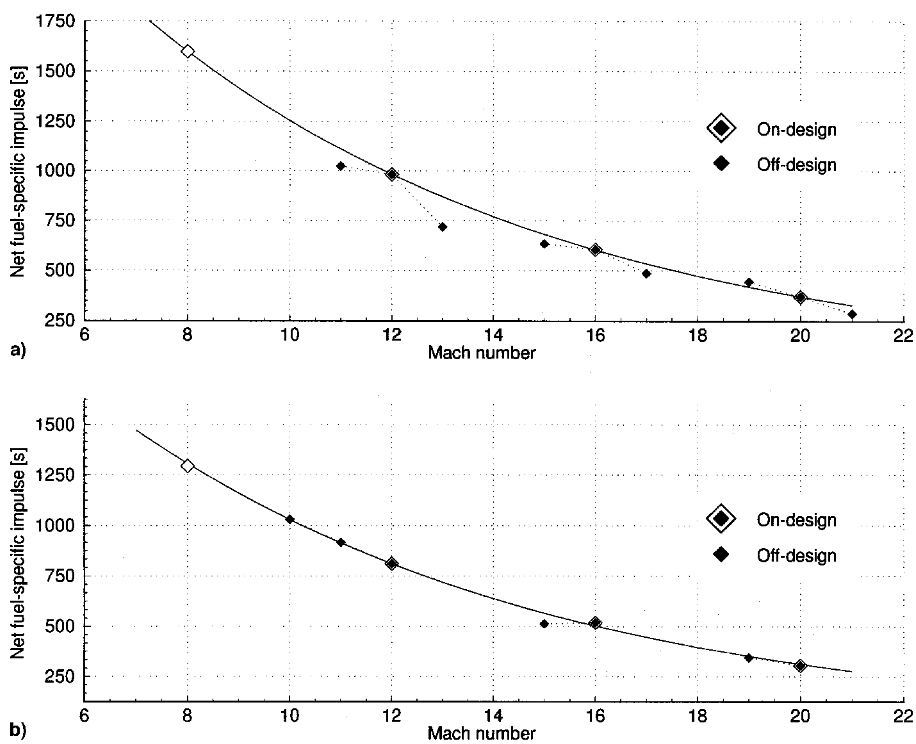

Fig. 11 Net fuel specific impulse of planar shcramjet configurations, q_{dyn} = 1400 psf: a) mixed- and b) external-compression shcramjet.

at off-design conditions. Of particular interest is the induction zone for the off-design operations at Mach 17, shown in detail in Fig. 9. Here, the third inlet shock intersects the shock formed at the leading edge of the detonation wedge, point D, about 1 cm above the cowl surface and 6 cm downstream of D. Chemical reactions begin about 9 cm downstream of this intersection point. The initiation of chemical reactions is delayed to about 15 cm downstream of point D, ~5 cm farther downstream than in the on-design case. Because of the modifications in combustor geometry mentioned earlier, Fig. 10 shows that for off-design operation at Mach 17, there is little difference in the combustor flowfield around the detonation wave near the nozzle entry section in comparison with the on-design flowfield (Mach 16).

Figure 11 plots the net fuel specific impulse for mixed- and external-compression shcramjets, with a uniform fuel/air distribution, operating at on- and off-design conditions for flight Mach numbers from 12 to 20. The solid curves represent the locus of points corresponding to on-design operation.[1] Data points not lying on the curve (solid symbols without an outline) are the performance values for off-design operation. Performance values for a single engine geometry operating at a lower-than-design flight Mach number, on-design, and higher-than-design Mach number are joined by dotted lines.

For both mixed- and external-compression shcramjets, the on-design curve shows that I_{sp} decreases as the Mach number increases. The figures show that I_{sp} deteriorates in the off-design operating regime, and more so for mixed-compression shcramjets than for external-compression shcramjets. Of note is the data point in Fig. 11b corresponding to the operation of the Mach 12 external-compression shcramjet at Mach 10. This was the only case considered for which the difference between on- and off-design Mach numbers was greater than 1. The figures show that the fuel specific impulse of mixed-compression shcramjets remains superior to that of external-compression shcramjets for off-design operation.

Conclusions

While there is a degradation in most overall performance parameters, shcramjets with extreme deviations from complete (homogeneous) fuel/air mixing have acceptable levels of performance; mixed-compression shcramjets being superior to shcramjets with external-compression inlets. It was also found that mixed-compression shcramjets produce more net thrust then external-compression shcramjets when operating at off-design flight conditions. For both types of engines, the relative loss of thrust at off-design conditions decreases as the flight Mach number increases. External-compression shcramjets are more sensitive to off-design operation than mixed-compression ones in their overall aerodynamic performance, such as lift and thrust to lift ratios. The ability to sustain adequate levels of thrust at different flight conditions is an essential feature of an accelerating body such as the shcramjet. The present study shows that thrust generation of the engine deteriorates when no changes to the engine geometry are made for off-design operation. It is reasonable to assume that thrust generation can be recovered with slight changes to engine geometry, particularly at the high end of flight Mach numbers where the shcramjet is believed to be superior to scramjets.

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