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EFFECT OF HEAT RELEASE ON HYPERMIXING FUEL INJECTOR PERFORMANCE IN A SUPERSONIC COMBUSTOR

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ABSTRACT

This paper presents a numerical investigation that provides a detailed study of heat release effects on the flow for two hypermixing fuel injectors designed for a supersonic combustor. Three injector configurations are compared: a swept compression-expansion ramp (SCER); a castellated blunt trailing edge, and a plane base injector. All injector configurations are strut mounted with hydrogen base-injection. A one-step reaction is used for all reacting cases. Details on near-field flow and mixing mechanisms with effects of heat release are discussed. It is found that heat release decreases mixing significantly in the near-field.

INTRODUCTION

One of the proposed propulsion systems for the next generation of aerospace planes is the supersonic combustion ramjet (scramjet). This propulsion system requires the mixing of fuel and oxidant at supersonic velocities. However, it is known that mixing at high Mach numbers is not very efficient (Gutmark, Schadow, and Yu, 1995). Significant efforts are therefore being undertaken to find ways to enhance supersonic turbulent mixing, particularly by modification of the fuel injector geometry.

Several mixing enhancement devices have been proposed. One such class of devices is termed hypermixers. Hypermixing involves the generation of streamwise vorticity to enhance mixing by increasing the interfacial surface area and the magnitude of gradients normal to the fuel-air interface (Davis, 1992).

Past studies have shown that heat release can have a significant effect on mixing layers (McMurtry et al., 1989). A direct numerical simulation study performed by McMurtry et al. found that baroclinic torque and thermal expansion generated by combustion in the mixing layer produces changes in the vortex structure, resulting in more diffuse vortices with lower rotation rates, and therefore decreased mixing.

Heat release has also been shown to decrease mixing enhancement produced by hypermixers (Riggins and McClinton, 1990). Heat release was found to increase the rates of decay of streamwise vorticity and cause strong pressure gradients, altering the vorticity flowfield (Eklund and Stouffer, 1994). However, some studies have found that mixing enhancement with streamwise vorticity was less sensitive to the effects of heat release than that of a planar mixing layer (Underwood and Waitz, 1996).

INJECTORS

The two hypermixing injectors, for which computations were performed, are shown in Fig. 1, alongside the plane base injector, which forms the datum for this study. The first hypermixing injector has a segmented, blunt trailing edge and is referred to here as the castellated injector. The second hypermixing injector is a mid-plane version of a swept compression-expansion ramp injector similar to that used by Davis and Hingst, (1991).

Earlier studies have shown that certain castellated trailing edge aerofoils have lower base drag in supersonic flow than their blunt trailing edge counterparts (Magi, 1990). The drag reduction is primarily due to the entrainment of fluid from the upper surfaces of the projections into the recessed regions. This geometry is similar to that of a straight expansion ramp. It is hoped that drag reduction and mixing enhancement by the hypermixing features of the geometry can be achieved simultaneously.

Swept ramps are known to enhance mixing via the production of pairs of large counter-rotating streamwise vortices (Davis, 1992). The swept compression-expansion ramp (SCER) should also produce a pair of large and very strong counter-rotating streamwise vortices, energised by the pressure difference between the faces of the compression and expansion ramps (Davis and Hingst, 1991).

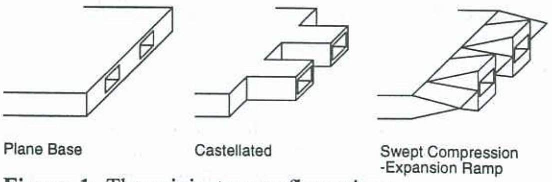

Figure 1: Three injector configurations.

NUMERICAL APPROACH

The supersonic combustor was divided into three computational domains as shown in Fig. 2: (1) the inlet, (2) the isolator and (3) the injector including 10 base heights (1 base height = 4.8 mm) downstream of the injector base. The outlet of each domain was used as an inlet for the next to obtain the highest grid resolution for the computer memory available. The end view in Fig 2. shows that only a quarter of one fuel jet was modelled making extensive use of planes of symmetry to reduce computation time.

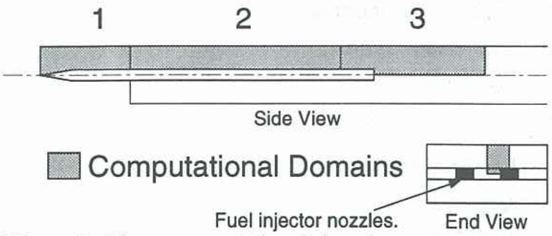

Figure 2: Three computational domains.

A three-dimensional, multi-domain flow solver CFD-ACE was used. CFD-ACE is a pressure-based code, which employs a cell-centred control-volume solution approach (CFDRC, 1997). A first-order upwind scheme was used for all computations. Turbulence was modelled using the k-ε model with both the turbulent Prandtl and Schmidt numbers set to equal 1.0. Combustion was modelled using a simple one–step water formation reaction. This model is valid when the mixing rate is slower than the reaction rates. This is known as mixing-limited combustion (Gaston et al., 1998). The model was also chosen to maximise the effect of heat release.

Grids were generated using CFD-GEOM, a structured /unstructured grid generator, supplied with CFD-ACE. Each computational domain contained approximately 200,000 cells.

Solution convergence criteria was the reduction of equation residuals by 4-5 orders of magnitude. However this was not achieved for the SCER injector reacting solution. Only 2-3 magnitudes were achieved due to instabilities in the base region of the injector. No grid convergence issues are addressed here due to computer memory limitations.

Flow Conditions

Flow conditions are summarised in Table 1.

Ho = 2.9 MJ/kg	Free-stream Conditions	Fuel Conditions ($\phi = 0.8$)
Mach No.	2.5	2.0
Pressure (kPa)	90	50
Temperature (K)	1230	160
Density (kg/m^3)	0.25	0.076
Velocity (m/s)	1710	1960

Table 1: Flow conditions.

These flow conditions are the same ones used for previous experimental investigation (Gaston et al., 1998). Air was used as the free-stream gas and hydrogen for the injected fuel.

PERFORMANCE PARAMETERS

Two parameters were used to assess the performance of the injector configurations in reacting and non-reacting flow-fields. The parameters were: mixing efficiency, η_m, and streamwise circulation Γ. Mixing efficiency is defined as the fraction of fuel that could react if complete combustion occurred without further mixing,

$$\eta_m = \frac{\int \rho U Y_R dA}{\dot{m}_j},$$

where Y_R is the mass fraction of fuel (H_2), that can react and m_j is mass flow rate of injected fuel. In regions with a lean mixture, Y_R is equal to Y_j, the mass fraction of fuel; in regions having a rich mixture, Y_R is equal to $f(1-Y_j)/(1-f)$ and where $f = 0.0293$ (Eklund and Stouffer, 1994). For the reacting cases Y_j is equal to $Y_{H2} + 0.126Y_{H2O}$, where Y_{H2} is the unburnt fuel mass fraction and $0.126Y_{H2O}$ is consumed fuel mas fraction.

The second parameter Γ, is a measure of mixing enhancement, which is particularly important to hypermixing and is defined as,

$$\Gamma = \iint \left(\frac{\partial v}{\partial z} - \frac{\partial w}{\partial y} \right) dydz,$$

(Lee et al., 1997).

RESULTS AND DISCUSSION

Figure 3 shows the mixing efficiency, η_m, calculated for the three injector configurations for both non-reacting and reacting solutions. This was calculated for the first 10 base heights from the exit of the injector.

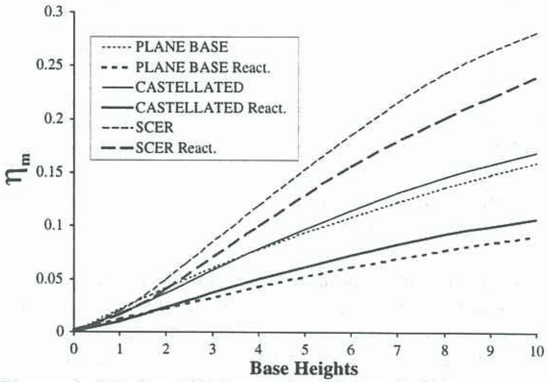

Figure 3: Mixing Efficiency for 10 base heights.

The figure clearly shows that the injectors exhibit a considerable decrease in mixing efficiency in the presence of heat release. However, this may be exaggerated by the use of the one-reaction equilibrium chemistry, which maximises heat release because only the exothermic water-formation reaction is used. The SCER injector seems to be less sensitive to the effects of heat release with only a 15% decrease in mixing, compared to decreases of 35% and 40%, respectively, for the castellated and plane-base injectors. This represents a drop 10% in mixing efficiency.

The greater effect of heat release experienced by the castellated and plane base injectors may be due to their more highly diffusion-dominated (molecular) mixing flow fields. This result compares well with experiments conducted by Underwood and Waitz (1996) which showed that planar mixing layer (diffusion dominated) was more sensitive to the effects of heat release than that of a lobed mixer.

The trends shown by the mixing efficiencies for the three injector configurations agree well with trends shown elsewhere through the agency of combustion-generated pressure rise (Gaston et al., 1998). These experiments showed little difference between the pressure fields produced using a castellated and a plane-base injector whereas the SCER injector produced much higher pressures.

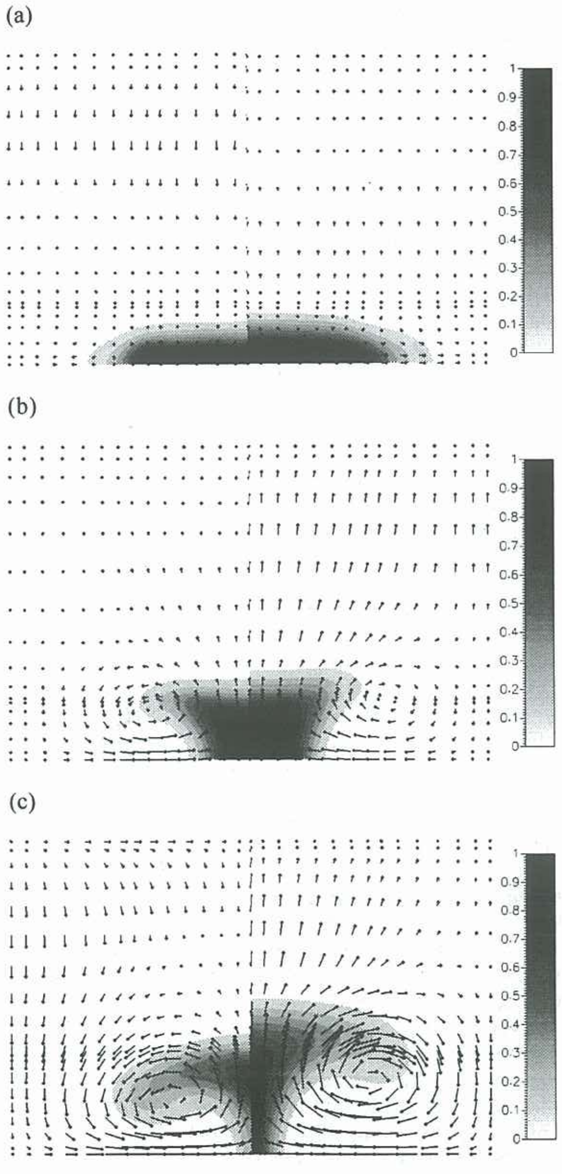

Figure 4: Mixture fraction contours and velocity vectors at 5 base heights from the injector exit with the non-reacting case on the left and the reacting case on the right (a) Plane Base, (b) Castellated and (c) SCER. A mixture fraction value of 1.0 is pure fuel and 0.0 corresponds to pure air.

A comparison between non-reacting and reacting flow fields is shown in Fig. 4. These are cross-plane images of mixture fraction contours overlayed by velocity vectors, obtained at 5 base heights.

Each image shows the effect of thermal expansion on the flow field (right side of images). The fuel jet has spread further and has a larger vortex core in the reacting case compared to the non-reacting case (Fig. 4 a and b). Even though the fuel interface is longer in the reacting case, lower mixing efficiencies are calculated (Fig. 3) due to the lower density in the reacting flow fields. Close examination shows that the maximum fuel fraction obtained is higher in all reacting cases.

Figure 4 b and c show the changes in vortex position and interaction with the fuel jet. In the non-reacting cases the vortex is closer to the fuel jet and the fuel jet is clearly more highly strained due to the closer proximity of the vortex. Not shown is the initial formation of the vortex, which is pushed away from the fuel jet due to high pressures cause by combustion in the base regions of the injectors.

The images of the plane-base injector (Fig. 4a), show that most of the mixing occurs laterally. This is caused by the large recirculation region at the base of this injector assisting the mixing of the fuel injected into it. The highly turbulent, low speed flow here allows a reasonable level of lateral mixing to occur. The castellated injector does not have a large recirculating base region near the injection nozzle, but the streamwise vorticity generated by the castellations enhances mixing to produce a similar overall level of mixing. Thus the explanation for the closely matched mixing efficiency of the castellated and plane-base injectors lies in the replacement of one mixing assistance mechanism by another.

The calculated streamwise circulation for the castellated and SCER injectors, is shown in Fig. 5. The plot shows approximately a 10% decrease in streamwise circulation for both injectors in the reacting case. However, at 5 base heights, the castellated injector seems to be slightly less affected. This is also shown by the velocity vector patterns of Fig. 4b, which are very similar for the non-reacting and reacting cases.

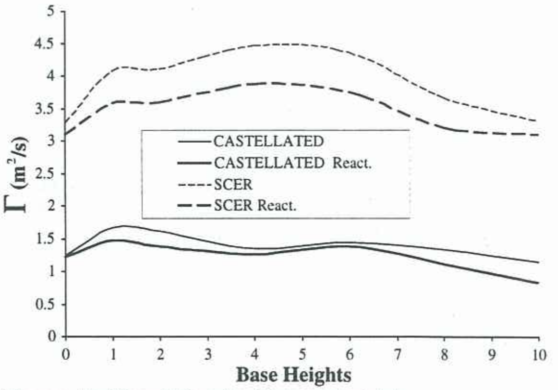

Figure 5: Circulation to 10 base heights

Figure 6 shows that heat release seems to have a significant effect on the development of vorticity in the SCER injector. From the magnitude and direction of the velocity vectors near the ramp sides it seems that injected fuel has been entrained into the recirculation zones beside the ramp. The resulting combustion in this region pressurises the side of the ramp. This causes a weaker vortex to form downstream, with its centre further away from the fuel jet (Fig. 4b and c). This phenomenon has been observed by others both numerically and experimentally (Eklund and Stouffer, 1994). This weakening and translation of the vortex is a possible mechanism for the reduction in mixing efficiency.

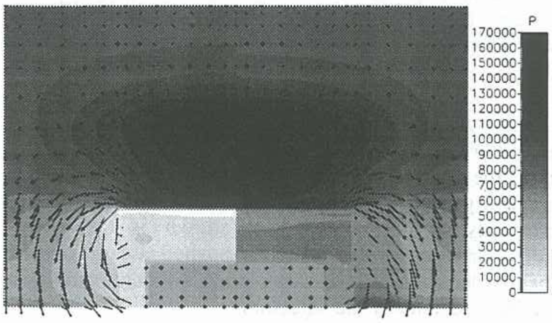

Figure 6: Pressure (Pa) contours and velocity vectors at the base of the SCER injector with the non-reacting case on the left and the reacting case on the right.

CONCLUSIONS AND FUTURE WORK

A numerical study of the effects of heat release on the near-field flows behind two hypermixing fuel injectors has been presented. Many of the near-field flow phenomenona appearing in the calculated flows have also been observed by other investigators (Underwood and Waitz, 1996). However, the flow-field studied here is more complicated in its vorticity generation mechanisms.

The conclusions of this study are as follows:

1) Significant reductions in mixing efficiencies due to heat release were calculated, up to 40% for the plane-base injector. This suggests that mixing studies in non-combusting flows are of limited use in deducing mixing performance in combusting flows.

2) Small reductions in streamwise vorticity of about 10% were also found. This suggests that heat release has a greater effect on diffusion-dominated flows (molecular mixing) than on vorticity-enhanced flows. Thermal expansion may be the mechanism responsible for this.

3) The lower mixing efficiency of the castellated and plane-base injectors in the reacting case might be explained by their much lower strained flow fields, which reduces their ability to feed combustion.

4) The plane-base and castellated injectors have similar mixing efficiencies even through their flow-fields are quite different. This seems to be due to one mixing mechanism, base recirculation being replaced by another, streamwise vorticity.

To gain a better understanding of the effects of heat release a finite-rate chemistry model needs to be used. This should provide more accurate knowledge of the flow field. The use of more realistic turbulent Schmidt and Prandtl numbers, as used by Riggins and McClinton (1990), may also help in providing more accurate results. As lower turbulent Schmidt and Prandtl numbers more accurately model the behaviour of supersonic mixing.

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