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Effect of Stream Temperature on Hypervelocity Reacting Mixing Layer

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Model free simulations have been carried out to study the effect of stream temperature on the growth and structure of the confined H_2/air hypervelocity mixing layers. Three different cases were investigated. In the first case, the Erdos experimental condition was simulated in which the upper stream (H_2) temperature is 103 K and the lower stream (air) temperature is 2344 K. In the other two cases the temperatures of both the streams are considered equal and they are 1200 K and 1500 K respectively. The mixing and combustion characteristics of a hypervelocity mixing layer have been studied by comparing the large scale structures of the flow. The temperature rise due to chemical reaction in the mixing layer is significantly low due to stretch effect. Upward shift of the reaction zone for 1200 K and 1500 K cases were observed compared to the Erdos experiment case. It is argued that the difference in the momentum ratios of the streams in the inflow plane is mainly responsible for this shift. High heat release contribute significantly in the wall pressure rise in the confined mixing layers.

Introduction

A vital part of the effort to develop advanced propulsion systems capable of sustaining hypersonic flight in the atmosphere is the ability to understand the complex mixing and combustion process inside a scramjet combustor. The prototype representation of the flow field inside the scramjet combustor is a supersonic reacting mixing layer. Even though this reacting mixing layer is geometrically simple, it can still be made to retain all of the fluid dynamical and chemical complexities present in the actual combustor flow field.

Supersonic reacting mixing layers were studied quite extensively in the last few decades, both experimentally[1–5] and computationally.[6–10] Most of the experiments were conducted at relatively low velocities and significant differences in compressibility and convective Mach numbers were achieved by varying the molecular weight of the gases. Erdos *et al.*[11] presented a very important experimental investigation of a 'clean' mixing layer coming out of a splitter plate at hypervelocity condition. In this experiment, the secondary stream (H_2) comes in contact with the primary stream (air) at the edge of the splitter plate in an enclosed test section of size 535 mm × 25.4 mm. Chakraborty *et al.*[12] have performed two dimensional Direct Numerical Simulation (DNS) for high speed confined reacting shear layer with finite rate chemical kinetics with seven species and seven reactions. Arguments have been provided for using a two dimensional calculation using the work of Lu and Wu,[10] Zhuang *et al.*[13] and others who have conducted the computational study of a high speed compressible mixing layer and shown that two-dimensional simulation is satisfactory for such a confined mixing layer. Good comparison of experimental wall pressure distribution with DNS results obtained was considered the basis of further investigations.

The temperature conditions at the inflow plane - 103 K for Hydrogen stream and 2344 K for the air stream considered in the experiment of Erdos *et al.*[11] - are very different from scramjet operating conditions. The reason for this observation is as follows. Hydrogen being a cryogenic can easily be exploited for its cooling capability, much needed in a hypervelocity vehicle. After the cooling process, its temperature can be as high as 800 - 1500 K depending on how it is used for cooling. A further advantage in raising the temperature of hydrogen is that the ignition process inside the combustor is helped considerably. Further, the air

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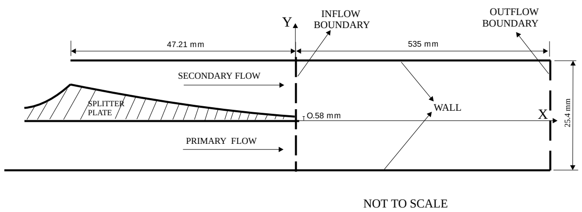

Fig. 1 Schematic Representation of experimental setup of Erdos et. al.[11] for which computations were done

stream will get heated due to the shock process in the air intake and can be expected to be at 1000 - 1500 K depending on the Mach number of the air stream. Hence simulations were carried out for two more cases where both the primary and secondary streams have the similar temperatures namely 1200 K and 1500 K respectively , while all other properties in the inflow plane are kept the same as the Erdos experimental condition. In this work we will analyze this Direct Numerical Simulation result to study the effect of stream temperatures on the thermochemical behavior of the hypervelocity mixing layer.

Analysis

In order to explore the thermochemical behavior of a confined supersonic mixing layer, Direct Numerical Simulation was performed. The results of the DNS calculations for the H_2/air confined supersonic mixing layer are given in the earlier work of the present authors .[12] The simulation was performed for the hypervelocity mixing layer experiment of Erdos *et al.*[11] In this experiment, the secondary stream (H_2) comes in contact with the primary stream (air) at the edge of the splitter plate in a enclosed test section of size 535 mm $\times$ 25.4 mm. The schematic experimental setup for which the computations were carried out is presented in Fig. 1. The Mach number and the temperature of the two streams are 3.99 and 2344 K (air) and 3.09 and 103 K (H_2) respectively. The convective velocity is 3000 m/s and the convective Mach numbers are 0.85 and 0.82 referred to H_2 and air streams respectively. The free shear layer experiments of Clemens and Mungal[14] suggest dominant three dimensional effects for this convective Mach number range and have been supported by the linear instability analysis[15,16] which have shown that oblique disturbances become more and more unstable as convective Mach number exceeds 0.6. *However, Tam and Hu[17] and Zhuang* et al.[13] *have shown that, for laterally confined mixing layers, the most unstable mode is the lowest order two-dimensional mode.* The principal point made in these papers is that the coupling between the motion of the shear layer and the channel acoustic wave produces a new instability mechanism in the supersonic range which originates from the wall confinement and is different from the classical Kelvin-Helmholtz instability. Zhuang *et al.*[13] have shown that the bounded two-dimensional modes are in good agreement with the experiments of Papamoschou and Roshko.[18] Lu and Wu[10] have performed two-dimensional simulations for a mixing layer with a convective Mach number as high as 1.77 citing the work of Tam and Hu[17] who studied the effect of confinement on the shear layer development in supersonic streams. These studies have shown that two-dimensional simulation is satisfactory for confined mixing layers. Apart from confinement effect, heat release effect also plays a vital role to make the most unstable mode two dimensional. The linear stability analysis of a reacting compressible mixing layer by Shin and Ferziger[19] has demonstrated that heat release makes the dominant mode two dimensional even in the high Mach number region and they have concluded that most unstable mode for reacting flow is two dimensional even if the instability mode is three dimensional (oblique) for the non-reacting case.

In the present work, both confinement and heat release effects are part of the physics implying that the role of large scale two-dimensional structures in modulating the chemistry-flow interactions is significant and can be understood from two-dimensional simulations.

As the experimental condition is far removed from the scramjet operating condition, specially with regard to the temperature of the streams, two more simulations were made by taking realistic stream temperatures. In these simulations, both the primary and secondary streams have similar temperature 1200 K and 1500 K respectively, while all other properties are kept the same at the inflow plane. The details of the inflow parameters of all the calculations are shown in Table 1.

The code used in the DNS is the SPARK2D combustion code developed at the NASA LaRC by Drummond and Carpenter[20] and has already been used in Sekar and Mukunda[21] and Mukunda.[7] It uses a 4th order compact MacCormack scheme with second order temporal accuracy. This choice represents a compromise between the accuracy of higher order numerical algorithms and the robustness and efficiency of lower order methods. The

Table 1 Inflow parameters of the cases with various stream temperatures.

Cases	Species	u (km/s)	T (K)	M	p (MPa)
Case 1	H_2	2.4	103	3.09	0.021
	Air	3.8	2344	3.99	0.021
Case 2	H_2	2.4	1200	5.63	0.021
	Air	3.8	1200	0.92	0.021
Case 3	H_2	2.4	1500	5.06	0.021
	Air	3.8	1500	0.83	0.021

Table 2 Elementary reactions for full chemistry computations.

No.	Reaction
1	$H_2 + O_2 \rightarrow OH + OH$
2	$O_2 + H \rightarrow OH + O$
3	$H_2 + OH \rightarrow H_2O + H$
4	$H_2 + O \rightarrow OH + H$
5	$OH + OH \rightarrow H_2O + O$
6	$OH + H + M \rightarrow H_2O + M$
7	$H + H + M \rightarrow H_2 + M$

code has been validated by computing a linearly unstable shear flow problem in the early stages of the growth. Carpenter and Kamath[22,23] have demonstrated that, with the compact schemes considered here, the growth rates with the initial profiles based on the eigenfunctions predict those from linear stability theory for free shear layers to within 1% for a time duration equal to about five times the sweep time of the flow field. This accuracy is adequate for the present computations needing a maximum of three sweep times - one sweep for clearing the flow field, and two more sweeps to collect statistical information and also check on the statistical invariance of the calculations.

The reaction rates for all the cases are calculated using Full Chemistry (FC) kinetics. A reaction mechanism involving seven species and seven reversible reactions[20,21] has been chosen for the full chemistry calculations. This reaction mechanism include the species H_2, O_2, H_2O, OH, H, O and N_2. The reaction steps and the rate parameters of the reactions are given in Table 2 and Table 3 respectively.

The boundary conditions set for the present problem are as follows: The no slip conditions and constancy of wall temperature are imposed on the wall. On the inflow stream are imposed velocity

Table 3 Reaction rate parameters for full chemistry computations.

No.	A	N	E/R, K
1	0.170×10^{14}	0	24230
2	0.142×10^{15}	0	8250
3	0.316×10^{08}	1.8	1525
4	0.207×10^{15}	0	6920
5	0.550×10^{14}	0	3520
6	0.221×10^{23}	-2	0
7	0.655×10^{18}	-1	0

fluctuations over a range of frequencies at total rms intensity of 0.3% of the mean velocity. The frequency has been normalized with the mean velocity to channel width ratio. The frequency range allows the mixing layer to grow as may happen in reality. The exit boundary condition is obtained by second order extrapolation and is considered satisfactory for this problem dominated by supersonic flow.

The calculation used a 1000 × 101 grid with grid stretching in high gradient zones - near interface, near splitter plate and near the walls. The grid independence of the results was established[12] by not only comparing the result of the simulation with different grids but also comparing the spectral content of fluctuation with different grids.

Results and Discussions

To find out the effect of stream temperature on the thermochemical behavior of the hypervelocity confined mixing layers, parametric studies were carried out by varying the temperatures of primary and secondary streams. As explained earlier, three different cases were considered. In the first case, the experimental conditions of Erdos *et al.*[11] were simulated, whereas in the second and third case temperatures of primary and secondary streams are considered equal and they are 1200 K and 1500 K respectively. As in the earlier study,[12] the computations were performed for three sweep times - one sweep for clearing the flow field and two more sweeps to collect statistical information and also to check on the statistical invariance of the calculation. One sweep of calculation is taken as the time the flow takes to cross the axial length of flow domain (535 mm) with its convective velocity. After the attainment of statistical steady state, velocities, density and the species mass fractions are gathered at all radial points of few axial locations at each time step over one sweep duration to enable statistical analysis.

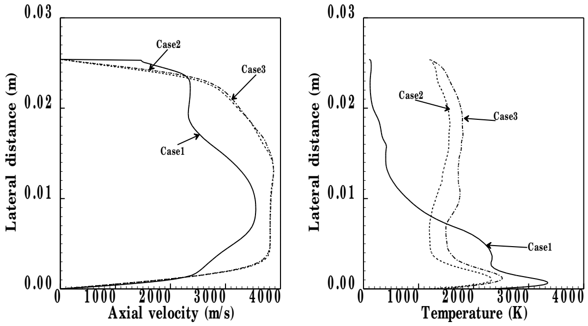

Fig. 2 Comparison of mean profiles with various stream temperatures at $x = 0.5$ m (a) Velocity (b) Temperature.

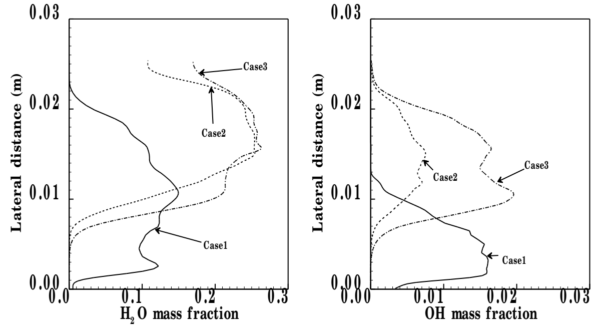

Fig. 3 Comparison of mean profiles with various stream temperatures at $x = 0.5$ m (a) H_2O mass fraction (b) OH mass fraction.

The comparison of the mean velocity and temperature profiles at an axial location of $x = 0.5$m from the splitter plate for the three cases are presented in Fig. 2. The reduction in the density due to increase in temperature is responsible for increase in velocity for case2 and case3 in the mixing layer. In the temperature comparison, for case1, where the upper stream temperature is at 103 K and lower stream temperature at 2344 K, the process of boundary layer growth in the lower wall raised the temperature to a value in excess of 3200 K. However because of significant mixing of large structures, the temperature in the mixing layer region decreased considerably. For the other two cases, barring the temperature rise in the air boundary layer region, the bulges in the temperature beyond 1200 K and 1500 K are due to exothermic chemical reactions, The increase in temperature is only about 200 - 300 K whereas the expected value due to local equilibrium (under diffusive conditions) is nearly 1400 K. This shows the enormous significance of stretch dominated effect discussed in the literature.[7]

The profiles of mean mass fraction of H_2O and OH for the three cases are compared in Fig. 3 at $x = 0.5m$ axial location.

It is very clear from the figures that while for case1 the reaction zone is near the middle of the mixing layer, there is considerable shift of reaction zones towards the upper wall for the other two cases. To find out the cause of this shift, the net momentum flow (M) for the two streams for all the three cases are compared in Table 4.

The momentum ratio $(M(A)/M(H_2)$ in case2 and case3 is very high compared to the momentum ratio 1.38 in the case1. This high momentum ratio is responsible for this upward shift.

The mean heat release rate profile for all the three cases at $x = 0.5m$ is compared in Fig. 4. The negative sign corresponds to exothermic reaction and positive sign correspond to endothermic reaction. In case1, high air temperature in the lower side caused the reaction to be endothermic because of dissociation process. The shift of reaction zone for case2 and case3 towards the upper wall is also visible in the figure.

Table 4 Net momentum flow(M) of the species with various stream temperatures.

Cases	Species	Momentum Flow (N) In plane	$M(A)/M(H_2)$
Case 1	H_2 Air(A)	4979 6907	1.38
Case 2	H_2 Air(A)	381 13914	36.52
Case 3	H_2 Air(A)	326 11798	36.19

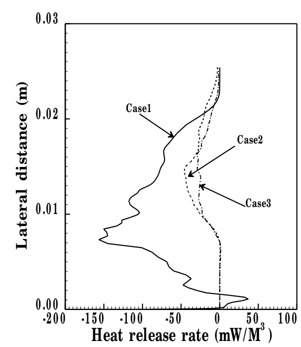

Fig. 4 Comparison of heat release rate mean profiles with various stream temperatures at $x = 0.5$ m.

The comparisons of surface pressures between these cases are presented in Fig. 5.

The no-reaction (NR) case result of case 1 is also presented in the figure to highlight the role of

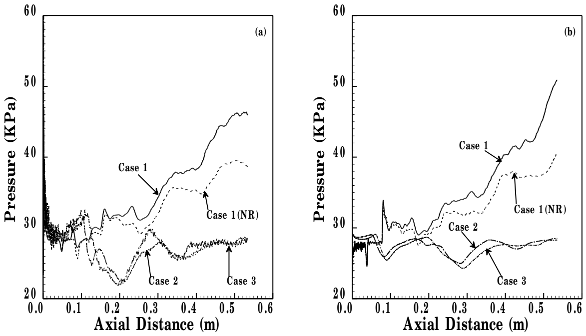

Fig. 5 Surface pressure comparison with different stream temperatures for (a) Lower wall (b) Upper wall.

heat release in the pressure rise phenomena. The high heat release and more shock reflections in the first case has caused the surface pressure to rise more compared to the other two cases where the reactions are weak and the rise in pressure is small.

Conclusions

Parametric studies were carried out by varying the stream temperatures to study its effect on the thermochemical behavior of the hypervelocity confined mixing layer. Three different cases were studied. The examination of the large scale structures reveal that temperature increase in the mixing layer is much lower compared to the expected value due to local equilibrium under diffusive condition. It is observed that due to high momentum ratio at inflow plane, the reaction zone for the cases corresponds to 1200 K and 1500 K shifted towards the upper wall. Heat release play a significant role in the wall pressure rise for the confined mixing layer.

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