Structural differences between the non-reacting and reacting supersonic planar mixing layer

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1 Introduction

The mixing layer has been studied extensively both experimentally and numerically, due to its fundamental importance to elucidation of the underlying physical mechanisms of compressible turbulence and the creation of next propulsion systems for hypersonic aircrafts. It consists of two parallel streams at different velocities, and the interface between the two flows is unstable and large scale eddies are formed because of the Kelvin-Helmholtz instability. Studies show that the mixing layer is self-similar within certain distance, its thickness grows linearly with downstream distance. However, its growth rate reduces with the increase of convective Mach number or the heat release of reacting mixing layers as a result of the decrease in pressure fluctuations[1-2].

Although mixing processes of three-dimensional structures are formed as the local Reynolds number increases, the two-dimensional structures continue to persist even at high speed [3]. The two-dimensional shear layer offers an opportunity to attain insights into the complex processes of mixing, therefore, it has also been investigated widely. Many subjects including a better understanding of the effects of compressibility, heat release, density ratios, ignition, equivalence and velocity on the instability characteristics and structure of two-dimensional mixing layer have been predicted.

Mahle et al [4] discerned that the effects of compressibility and heat release on mixing layers are in a similar fashion even their physical mechanisms are different. Pickett and Ghandhi [5] investigated experimentally the structure of a reacting hydrocarbon-air planar mixing layer, and found the inlet stream conditions affected the chemistry did not appear to cause significant changes in the overall mixing layer structure. The effect of stream temperature on the growth and structure of a hypervelocity mixing layers have been simulated numerically in Ref.[6], and found that the temperature rise due to chemical reaction in the mixing layer is significantly low

The purpose of this study is mainly to examine the effects of reaction and convective Mach number flows on the structure of a spatial evolving supersonic mixing layer. Large eddy simulation (LES) is used to investigate a spatially developing supersonic planar mixing layer.

2 LES of compressible mixing layers

LES of inert and reacting spatially evolving mixing layers are performed at convective Mach numbers *Mc*=0.3.

The governing equations for LES are obtained by applying Favre filtering to the 2-D compressible reacting Navier-Stokes equations. The inviscid derivatives are computed using a fifth-

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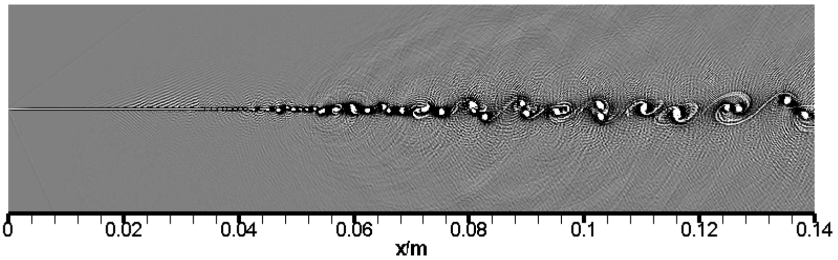
order WENO scheme [8]. Viscous fluxes are discretized by means of a second order accurate-centered scheme. The fourth-order Runge-Kutta scheme is used for the time integration. Pressure outlet conditions are imposed for both upper and lower boundary and a zero-gradient condition is enforced at the outflow boundary. Supersonic inflow boundary conditions are enforced. The mixing layer is formed by merging initially parallel air and hydrogen streams. The upper stream of the mixing layer is hydrogen, and the other is air. The temperature and pressure are chosen as the same for two streams. No pressure, density and Temperature gradient imposed for the calculations. The initial hydrogen and air flow Mach number are chosen as 1.3 and 1.1, respectively, which leads to a convective Mach number of 0.3.

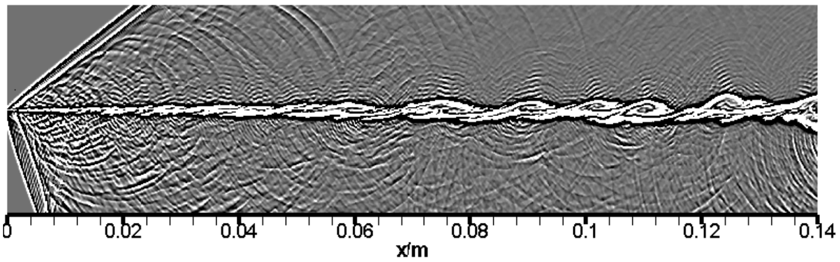
3 Numerical results and discussions

Figure 1 shows instantaneous numerical shadowgraph of (a) non-reacting and (b) reacting mixing layers at t=0.32ms. It is clear that the two streams mix, which leads to the formation of the spatial development of mixing layer. The mixing layer consists of large-scale structures which grow linearly with the increasing distance. For the reacting case, the layer thickness is larger at the beginning, (Figure 1.b), but its growth rate is small, which results in its thickness is smaller than the non-reacting case after a distance of about 0.12m. This slow growth rate of the mixing layer thickness due to the heat release agrees well with corresponding experimental and numerical results. On the other hand, the Mach waves and acoustical waves are stronger and more irregular for the reacting case due to the combustion expansion.

Figure 2 displays the typical acoustic wave contours of one large eddy in (a) non-reacting and (b) reacting mixing layers at t=0.32ms. The blue line means the positive value while the red for negative. In no-reacting case, each eddy is a typical quadrupolar source (Figure 2.a), which also agrees well with the results of Ref.[7]. However, for the reacting case, the eddy is kind of a monopole source (Figure2.b).

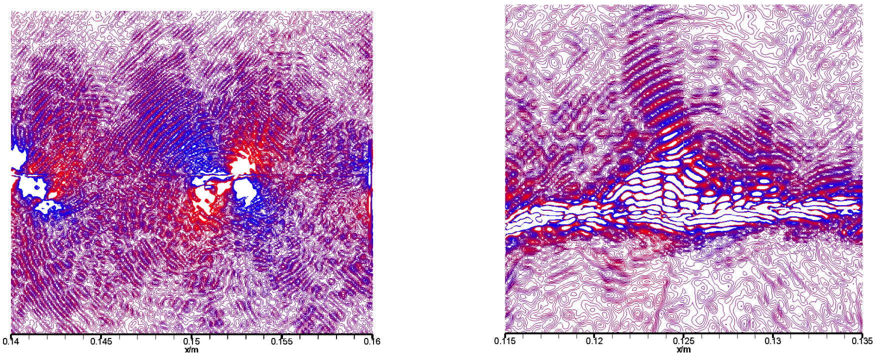


(a) Non-reacting mixing layer



(b) Reacting mixing layer

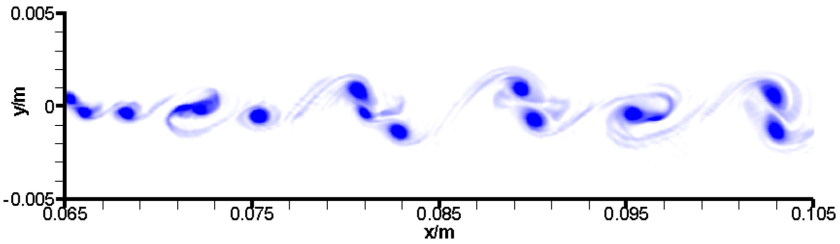
Figure 1. The instantaneous numerical shadowgraph of (a) non-reacting and (b) reacting mixing layers at t=0.32ms.



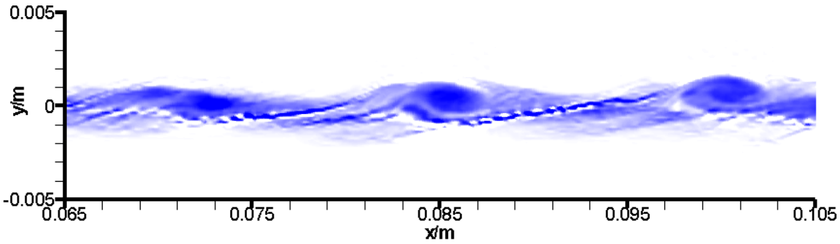
(a) Non-reacting (b) Reacting

Figure 2. The typical acoustic waves contours of one large scale eddy in (a) non-reacting and (b) reacting mixing layers at t=0.32ms.

The instantaneous vorticity contours of both reacting and non-reacting mixing layers are illustrated in Figure 3, respectively. For the no-reacting case, eddies are only negative vorticity (clockwise) and appear to spin and pairing more vigorously (Figure 3.a). However, in the reacting case, the size of eddies in streamwise increase due to the volumetric expansion, even the large eddies are negative, there are positive vorticity appearing on the outskirts of low side. Eddy pairings appear to be suppressed, which leads to the reduction of the growth rate of the mixing layer downstream the roll-up stage (Figure 3.b).



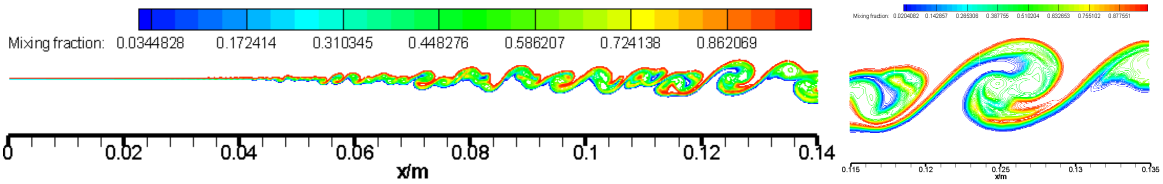
(a) Non-reacting mixing layer



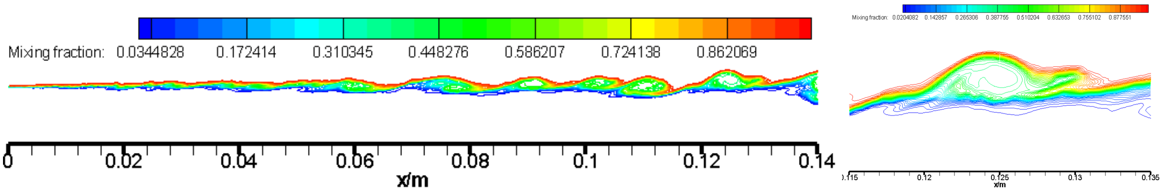
(b) Reacting mixing layer

Figure 3. The instantaneous vorticity contours of (a) non-reacting and (b) reacting mixing layers at t=0.32ms.

The effects of reaction on the mixing process can be expressed with the mixture fraction. Figure 4 presents the instantaneous mixture fraction contours of (a) non-reacting and (b) reacting mixing layers at t=0.32ms. A significant change occurs between these two cases. In no-reacting case, the air and hydrogen are entrained to the other side of the layer and mixed well at the center of vortex. However, in the reacting case, due to the flame expansion, the rolling up process is weaker, the air and hydrogen cannot be entangled to the other side, and they mixed rather well along the center line of the mixing layer. The temperature contours of reacting mixing layer are plotted in Figure 5. The flame can be located within the mixing layer around its center line, the mixed area, and their combustion area is enlarged within the vortices.



(a) Non-reacting mixing layer



(b) Reacting mixing layer

Figure 4. The instantaneous mixture fraction contours of (a) non-reacting and (b) reacting mixing layers at t=0.32ms.

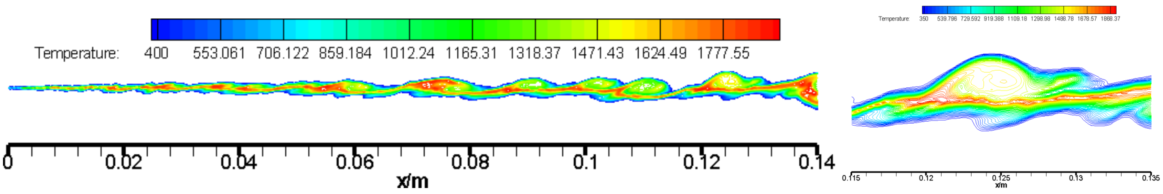
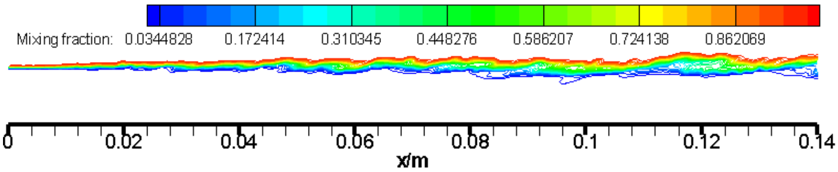
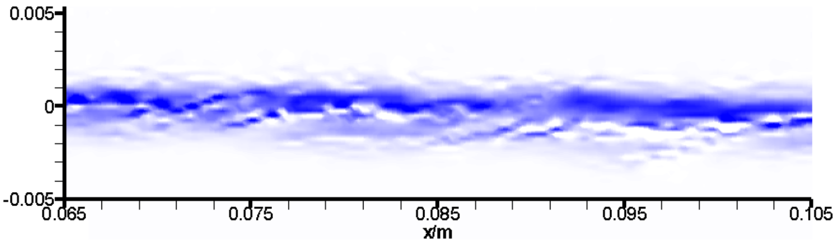


Figure 5. The instantaneous temperature contours of reacting mixing layers at t=0.32ms.

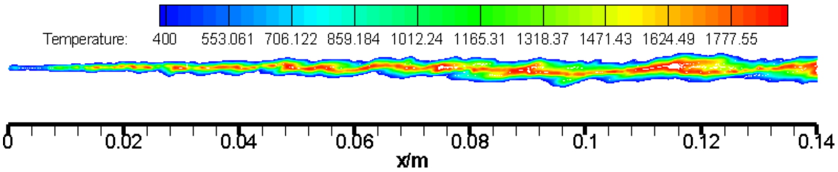
The effects of the increased pressure of two inflow streams on the reacting mixing layer structure are also investigated numerically. The mixture fraction, vorticity and temperature contours are shown in Figure 6. Compared to the above figures of reacting mixing layer, it is clear that, with the increase of inflow pressure (p_0=1.5atm), the mixing layer is pressed, and its thickness reduced further (Figure 6.a), and there are no clear large eddies appeared within the layer. However, compared to Figure 5, there are no distinct differences for the location of top temperature (the mixed area ,around the shear layer centerline), even its shape changed.



(a) Mixture fraction



(b) Vorticity



(c) Temperature

Figure 6. The mixture fraction, vorticity and temperature contours of reacting mixing layers with the increased inflow pressure.

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