NUMERICAL SIMULATION OF SUPERSONIC REACTING MIXING LAYER*

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ABSTRACT: In this paper, the supersonic chemically reacting mixing layer is simulated with the third order ENN scheme, based on the Navier-Stokes equations, containing transport equations of all species. The numerical results show that the thickness of mixing layer increases gradually along the flow direction, and that the Kelvin-Helmholtz instabilities may not exist in mixing layer flows.

KEY WORDS: reacting mixing layer, N-S equations, numerical simulation

1 INTRODUCTION

It is well known that the hydrogen-fueled scramjet engine are expected to be effective propulsion systems for high speed vehicle. In order to gain a detailed understanding of the complex flowfield present in the engine over a range of flow conditions, numerical simulations have been shown to be a valuable tool. The computational fluid dynamics not only play a major role for flowfields which wind tunnels cannot fully simulate and in which measurements are difficult to obtain but also provide flow details that are not available from experiment.

The flow field in a scramjet engine is governed by the full Navier-Stokes equations, containing transport equations of all species and reactions. It is almost impossible to carry out the computation of the combusting flows in a whole engine in detail due to the limition of computer source. In addition, the reaction in the combustor always takes place in the mixing layer, and there also exist the difficulties due to flow mechanism and combustion. Hence, two-dimensional reacting mixing layer is a suitable model problem for the study of this supersonic reacting flows.

In the past, many researchers focused their attentions on nonreacting mixing layer\cite{1,2,3}, but many important flow characteristics are the same for both reacting and nonreacting flows. At present, a majority of the studies on chemically reacting mixing layers have been carried out at subsonic rather than supersonic speeds. Keller\cite{4}, Mungal\cite{5} and Boradwell\cite{6} experimentally studied the reacting mixing layer. Reacting mixing layer studies using analytical or numerical approaches have also been carried out. Carrier, Fendell and Marble\cite{7} used a singular perturbation technique to modify their Burke-Schumann thin flame solution for a more realistic finite-thickness reaction zone in a mixing layer. Riley\cite{8} directly simulated a subsonic, temporally developing and mixing layer. Moreover, Menon\cite{9} studied the

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stability of a laminar premixed, spatially developing, supersonic mixing layer undergoing chemical reaction. Drummond[16] also studied the two-dimensional reacting mixing layer in detail and analysed the Kelvin-Helmholtz instability. In the present work, a chemistry model suitable for combusting flow computation is adopted to simulate the supersonic reacting mixing layer and the flow structures in supersonic reacting mixing layer are described, and the Kelvin-Helmholtz instability are studied.

2 THEORY

2.1 Governing Equations

The full Navier-Stokes equations, containing transport equations of all species are expressed in nondimensional form in generalized curvilinear coordinaties (τ, ξ, η) as

\[
\frac{\partial \mathbf{U}}{\partial \tau} + \frac{\partial \mathbf{E}}{\partial \xi} + \frac{\partial \mathbf{F}}{\partial \eta} = \frac{1}{Re} \left( \frac{\partial \mathbf{E}_v}{\partial \xi} + \frac{\partial \mathbf{F}_v}{\partial \eta} \right) + \mathbf{S}
\]

where,

\[
\mathbf{U} = \mathbf{U} / J \\
\mathbf{E} = (\xi U + \xi_x E + \xi_y F) / J \\
\mathbf{F} = (\eta U + \eta_x E + \eta_y F) / J \\
\mathbf{E}_v = (\xi_x E_v + \xi_y F_v) / J \\
\mathbf{F}_v = (\eta_x E_v + \eta_y F_v) / J
\]

\( U \) and fluxes are given by

\[
\begin{align*}
\mathbf{U} & = [\rho, \rho u, \rho v, p, p_f]_T \\
\mathbf{E} & = [\rho u, \rho u^2 + p, \rho u v, \rho H u, \rho f_i u]_T \\
\mathbf{F} & = [\rho v, \rho u v, \rho v^2 + p, \rho H v, \rho f_i v]_T \\
\mathbf{E}_v & = \left[0, \tau_{xx}, \tau_{xy}, \nu \tau_{xx} + \nu \tau_{xy}, \beta_3 \rho D_{im} \frac{\partial f_i}{\partial x} \right]^T \\
\mathbf{F}_v & = \left[0, \tau_{xy}, \tau_{xy}, \nu \tau_{xy} + \nu \tau_{yy}, \beta_3 \rho D_{im} \frac{\partial f_i}{\partial y} \right]^T \\
\mathbf{S} & = [0, 0, 0, 0, S_i]_T
\end{align*}
\]

where,

\[
\begin{align*}
H & = (e + p) / \rho \\
e & = \sum h_i f_i - p + \frac{1}{2} \rho (u^2 + v^2) \\
h_i & = \int_{T_r}^{T_c} \mathcal{C}_{pi} + h_{io} \\
q_x & = \beta_2 k \frac{\partial T}{\partial x} + \rho \sum \beta_3 D_{im} h_i \frac{\partial f_i}{\partial x} \\
q_y & = \beta_2 k \frac{\partial T}{\partial y} + \rho \sum \beta_3 D_{im} h_i \frac{\partial f_i}{\partial y}
\end{align*}
\]