대와류모사 기법과 확률밀도함수를 이용한 스크램제트 연소부에서의 연소 현상 연구

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Large-Eddy Simulation based Eulerian PDF Approach for the Simulation of Scramjet Combustors

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ABSTRACT

A probability density function (PDF) approach to account for turbulence-chemistry interaction in the context of large eddy simulation (LES) based simulation of scramjets is developed. To solve the high-dimensional joint-composition PDF transport equation robustly, the semi-discrete quadrature method of moments (SeQMOM) is recently proposed [1]. The SeQMOM approach addresses key numerical issues in LES related to the inaccuracies in computing filter-scale gradients, enabling an efficient and numerically consistent solution of the PDF transport equation. The computational tool is used to simulate a cavity- stabilized Mach 2.2 supersonic combustor.

Key Words : Large-eddy simulation, semi-discrete quadrature method of moments (SeQMOM), probability density function, scramjet combustor

Predictive models for supersonic combustion will provide a reliable and inexpensive pathway for designing high-speed vehicles such as scramjet. In the recent past, the LES methodology has emerged as a viable tool for modeling turbulent combustion [2]. LES computes the large scale mixing process accurately, thereby providing a better starting point for small scale models that describe the combustion process. In fact, combustion models developed in the context of RANS (Reynolds-averaged Navier-Stokes) equations exhibit better predictive capability when used in the LES framework [2].

In LES, transport equations for filtered variables are solved on a computational grid. Therefore, filtered energy equation as well as species mass fractions equations have the combustion-generated energy source terms. However, the filtered source cannot be the source calculated using filtered variables which are easily accessible in LES. Meanwhile, the filtered source term can be closed if probability density function (PDF) of the variables are known.

The transported probability density function (PDF) approach is a powerful technique for large eddy simulation (LES) based modeling of scramjet combustors [3]. In this approach, a high-dimensional transport equation for the joint composition-enthalpy PDF needs to be solved. Quadrature based approaches provide deterministic Eulerian methods for solving the joint-PDF transport equation. The direct quadrature method of moments (DQMOM) is one quadrature-based approach developed for modeling combustion [4]. The DQMOM has been successfully implemented for general combustion configurations include supersonic combusor [5] and spray reaction problems [6].

However, DQMOM approach is shown to generate inconsistent evolution of the scalar moments. Further, gradient-based source terms that appear in the DQMOM transport equations are severely underpredicted in LES

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leading to artificial mixing of fuel and oxidizer. To overcome these numerical issues, a new approach called SeQMOM has been proposed [1]. In this method, moments of the thermochemical compositions are solved and find a set of weights and abscissas that reproduce selected moments of the PDF accurately.

The computational tool is used to simulate a cavity-stabilized Mach 2.2 supersonic combustor (Fig. 1). The LES-SeQMOM approach captures the pressure profiles qualitatively, in spite of the large uncertainties in the boundary conditions (Fig. 2). Further, this flow configuration is found to exhibit low-frequency dynamics that lead to oscillatory motions of the shock-system inside the combustor. Detailed analyses of the LES data are used to describe the physical mechanism leading to these oscillations. In fact, with reactions, cavity-based (Fig. 3(a)) and isolator-based shock structures (Fig. 3(b)) repeat. Not only shock structure (Fig. 3), reaction strength is also different for the two reaction modes (Fig. 4). The oscillatory reactive motion also occurs in the experiment while the frequency shows some discrepancy to the LES results.

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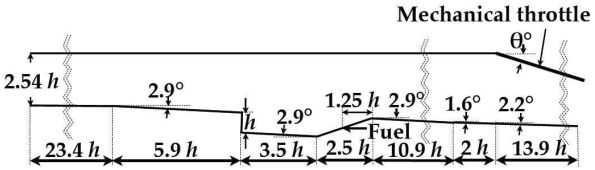


Fig. 1 Schematic of the flow configuration. All dimensions are normalized by cavity height h = 16.5 mm.

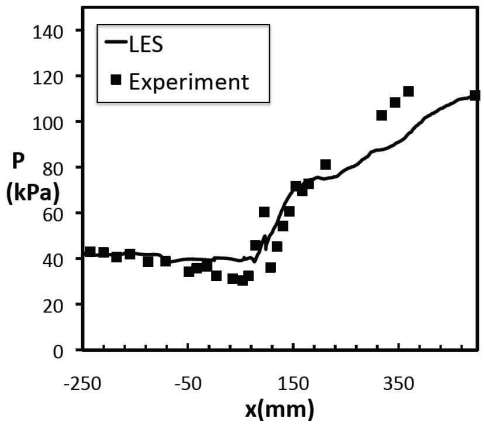


Fig. 2 Mean pressure profiles along the lower wall for non-reacting case.

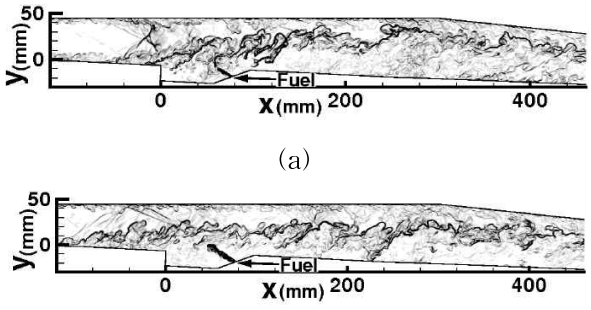
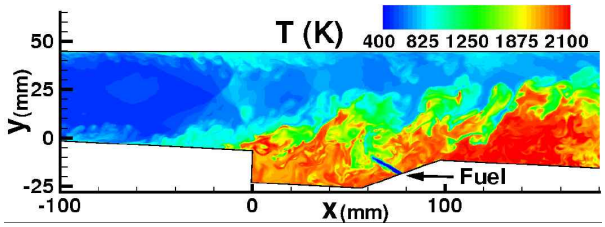
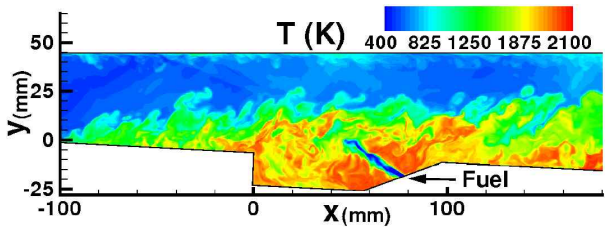


Fig. 3 Instantaneous contours of density gradient for (a) cavity-based and (b) isolator-based shock structure location.



(a)



(b)

Fig. 4 Instantaneous snapshots of temperature for (a) cavity-based and (b) isolator-based shock structure location.