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Simulation of Two-Dimensional Scramjet Combustor Reacting Flow Field Using Reynolds Averaged Navier-Stokes WENO Solver

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Abstract. The non-equilibrium chemical reacting combustion flows of a proposed long slender scramjet system were numerically studied by solving the turbulent Reynolds averaged Navier-Stokes (RANS) equations. The Spalart-Allmaras one equation turbulence model is used which produces better results for near wall and boundary layer flow field problems. The lower-upper symmetric Gauss-Seidel implicit scheme, which enables results converge efficiently under steady state condition, is combined with the weighted essentially non-oscillatory (WENO) scheme to yield an accurate simulation tool for scramjet combustion flow field analysis. Using the WENO schemes high-order accuracy and its non-oscillatory solution at flow discontinuities, better resolution of the hypersonic flow problems involving complex shock-shock/shock-boundary layer interactions inside the flow path, can be achieved. Two types of scramjet combustor with cavity-based and strut-based fuel injector were considered as the testing models. The flow characteristics with and without combustion reactions of the two types combustor model were studied with a transient hydrogen/oxygen combustion model. The detailed results of aerodynamic data are obtained and discussed, moreover, the combustion properties of varying the equivalent ratio of hydrogen, including the concentration of reacting species, hydrogen and oxygen, and the reacting products, water, are demonstrated to study the combustion process and performance of the combustor. The comparisons of flow field structures, pressure on wall and velocity profiles between the experimental data and the solutions of the present algorithms, showed qualitatively as well as the quantitatively in good agreement, and validated the adequacy of the present simulation tool for hypersonic scramjet reacting flow analysis.

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1 Introduction

The scramjet propulsion system can be used in the global high-speed transport, as well as significantly reducing the cost of satellite or spacecraft launch. Scramjet with its superior performance is extremely useful in the future national defense and can improve human livelihood. A typical scramjet propulsion system consists of five major components: internal inlet, isolator, combustor, internal nozzle and the fuel supply subsystem. The flow field in scramjet combustor is highly complex, in which the fuel-air mixing, flame stability and completion of combustion are all occurred and completed in combustor which limited the order of length one meter and the residence time of mixing is the order of milliseconds. Therefore, having an efficient fuel-air mixing and combustion of fuel with air at supersonic speeds without significant pressure loss are the important design specifications [1]. According to the references [2, 3], the flow structures of complex shock waves, viscous shear layers and its interactions in combustor flow could effectively aid fuel-air mixing but also lead to pressure loss. The incomplete mixing (or incomplete combustion) was the main factor leading to the thrust loss. Hence the increasing need to develop a system that effectively integrates fuel injection and flame holding for supersonic combustion exists.

Cavity flame holders have been proposed in recent years as a new concept for flame holding and stabilization in supersonic combustors. Some recent publications have brought to light the subject of cavity flows and their relevance to flame holding in supersonic combustion engines [4–6]. The cavity-based combustor has attracted considerable attention due to its characteristics of low total-pressure loss and air/fuel mixing enhancement. Most of the studies of cavity-based combustor have been done by numerical tools with or without chemical reaction [7–9]. Another new concept for flame holding was strut injector, which offers a possibility for parallel injection without causing much blockage to the incoming stream of air and also fuel can be injected at the core of the stream. Gerlinger and Bruggemann [10] conducted a numerical investigation of hydrogen injection from strut to study the effects of lip thickness of the injector in mixing. Tomioka et al. [11, 12] studied the effects of staged injection from struts. Many experimental and numerical analysis have been reported during the last few decades with respect to the characteristics of the complex flow field [13]. However, a numerical analysis on the cavity flame holder flow and strut injector flow for combustion is in high demand. The key performance parameters of scramjet engine can be determined from the CFD analysis are thrust, viscous drag, specific impulse and combustion efficiency. And also, configuration optimization using multi-variant optimization method can be performed for the design