RANS MODELING AND SIMULATION OF TURBULENT COMBUSTION IN A SCRAMJET

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Abstract

In the present work, we present a unified model for scramjet combustion that is more predictive than existing models. Emphasis is laid on modelling the interaction between chemistry and turbulent hypersonic flow. To that end, a detailed hydrogen-oxygen reaction mechanism is taken into account. In the numerical simulations a flamelet model and, alternatively, a CMC model is employed.

1. INTRODUCTION

Hypersonic propulsion using supersonic combustion ramjet (scramjet) technology offers the possibility of high speeds and fuel efficiencies. Therefore, current aerospace technology development contains several areas of scramjet application, the most outstanding example being reusable launch vehicles for space applications. The physico-chemical processes occurring in scramjets – viz., hypersonic flow, turbulence, and combustion chemistry – and especially the interaction between them are particularly complex and hence models of these processes are subject to ongoing worldwide research – see, e.g., [1–6] for some recent references on computational work. Unfortunately, due to the interdisciplinary nature of scramjet physics, most of the models contain tuning parameters which renders them non-universal. Thus, today's CFD models for scramjet applications are not really predictive, in particular not at higher flight Mach numbers. For instance, at Mach 8 an error of 5 % on nozzle performance leads to a reduction of 35 % in net thrust.

In the present work, we present a unified model for scramjet combustion that in view of combustion chemistry is more predictive than existing models. Specifically, emphasis is laid on modelling the interaction between chemistry and turbulent hypersonic flow taking detailed chemistry into account. For the numerical solution of the underlying compressible, hypersonic combustion problem, a powerful, self-adaptive, unstructured-mesh computer code has been developed that takes detailed combustion chemistry into account. The numerical results show good agreement with experimental data, in particular with respect to the flow field including location and strength of shock waves, and to the fields of the scalar variables that describe, and quantify, the scramjet combustion.

2. MODEL AND GOVERNING EQUATIONS

In the following subsections, we briefly describe the governing equations and the components of the overall model. Further details will be presented in the poster session.

2.1 Fluid Dynamics

The principal governing equations are the Favre averaged conservation equations for overall mass, momentum and energy, in two-dimensional form. Fluid mechanical closure is achieved by applying the usual eddy-viscosity, Boussinesq-type of approximation to the turbulent diffusive terms in the governing equations, in combination with the standard k-epsilon turbulence model. Depending on the chemistry model (see Sec. 2.3), these equations have to be supplemented by further governing equations.

2.2 Thermodynamics

Thermodynamic properties, such as internal energy, enthalpy, and constant-pressure specific heat, are evaluated based on fundamental thermodynamic theories. Each thermodynamic property can be conveniently expressed as the sum of the ideal-gas counterpart at the same temperature and a departure function that accounts for the dense-fluid correction. Specifically, in the present study, a modified Soave–Redlich–Kwong (SRK) equation of state [7,8] is chosen due to its ease of implementation and wide range of validity in modeling the fluid p–V–T behavior, except in proximity to the critical point [9].

The thermodynamic data are subjected to polynomial fits, which can easily be accessed and processed by the numerical solver.

2.3 Chemistry

Two alternative models of non-premixed turbulent combustion have been used. The first is the classical flamelet model of non-premixed turbulent combustion. For an overview of that model including

historical issues, [10] may be consulted. The required flamelet library was constructed using COSILAB [11]. The second model of non-premixed turbulent combustion used herein is the CMC model (CMC = conditional moment closure), which is similar to the RIF model [12]. For an overview of the CMC model, [13] may be consulted. Both the CMC and the flamelet model allow detailed chemistry to be taken into account. Herein, a detailed hydrogen-oxygen mechanism has been used [14].

In case of the flamelet model, the governing equations mentioned in Sec. 2.1 have to be complemented by a governing equations for the mixture-fraction mean and variance, respectively. In case of the CMC model, the governing equations mentioned in Sec. 2.1 have to be complemented by the complete set of Favre-averaged species conservation equations. Since the CPU time required for the numerical solution of a problem increases approximately linearly with the number of species conservation equations, the CMC model is a relatively expensive model to use.

3. RESULTS

Initially the code was validated using a series of subsonic, transonic and supersonic test problems, ranging from simple subsonic channel and pipe flow to transonic flow in a Laval nozzle. Computations for a scramjet engine were then carried out for a geometry that diverges in the main flow direction. At the left boundary of the domain, a supersonic flow of air was provided into which slightly downstream gaseous hydrogen is injected. Downstream of the fuel injection location, a turbulent mixing layer is formed in which ignition occurs, and in which a complex shock-wave pattern develops.

Computations were carried out for a range of Mach numbers with both the flamelet and the CMC model. Both chemistry models were found to capture the combustion phenomena within the complex wave pattern rather well. In the computations, up to four level of local grid refinement were realized. Final computational grids contain several hundred thousand triangular cells.

Graphical representations of selected results will be presented during the poster session.

4. LITERATURE

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