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Incipient thermal choking and stable shock-train formation in the heat-release region of a scramjet combustor. Part II: Large eddy simulations

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ABSTRACT

The flow in the HyShot II scramjet combustor is studied using large eddy simulations (LES). The computations are made feasible by two important modeling ingredients: an equilibrium wall-model and a flamelet-based combustion model. The first objective of the study is to assess the accuracy of this modeling approach through a validation study. Comparisons are made between simulation results and those from shock-tunnel experiments at nominal flow conditions, with favorable agreement. The second objective is to study the flow for increased fuel/air equivalence ratios (ERs). A qualitative change in the flow occurs for ER $\gtrsim$ 0.39, with the appearance of a seemingly stable combustor shock-train, similar to standard isolator shock-trains, but occurring spatially co-located with the combustion and heat release. This behavior accurately reproduces that seen in an accompanying experimental study. A detailed flow analysis identifies the factors contributing to the stabilization of the shock-train, and estimates are made of its effect on the overall combustor performance.

1. Introduction

The supersonic combustion ramjet (scramjet) is a theoretically efficient means of propulsion for atmospheric flight at Mach numbers above about 5. Despite the simplicity of the scramjet concept, however, there are major technical challenges associated with developing a working scramjet-powered vehicle. As the core airflow remains supersonic throughout the engine flowpath, injection, mixing, and combustion of the fuel must take place on very short time-scales. Moreover, since a high-speed air-breathing vehicle must operate over a wide range of Mach numbers, to reduce system complexity it is highly desirable that the scramjet-based engine component exhibits good performance throughout this spectrum of conditions, not just at the high Mach numbers to which a pure scramjet is best suited [1].

This latter requirement has led to the development of the dual-mode concept [2], in which an isolator (typically a constant-area diffusor) is introduced into the scramjet flowpath between the intake and the fuel-injection location. This isolator serves to house a precombustion shock structure when the engine is operating away from nominal scramjet (i.e., purely supersonic) conditions. Such a shock structure may be brought about in one of two ways [3,1]. First, at lower flight Mach numbers, the combustor heat release is tailored so that the flow becomes choked (i.e., the Mach number is reduced to unity), causing a normal shock-train with a subsonic core to form in the isolator (see Matsuo et al. [4] for a review of shock-train phenomena). In this way, the engine operates as a traditional ramjet, with the area change downstream tailored to re-accelerate the flow to supersonic conditions. As the flight Mach number increases, however, the stagnation pressure loss associated with a normal shock-train would reduce the cycle efficiency substantially; furthermore, the pressures and temperatures (the latter resulting in dissociation and a loss of available chemical energy) produced by decelerating the flow to subsonic conditions become increasingly undesirable [3,5]. Thus, in this regime the dual-mode engine operates in scramjet mode, with

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the core flow supersonic throughout. Nevertheless, it may still arise that the adverse pressure gradient inside the combustion chamber causes the wall boundary layers to separate, forming an oblique shock-train (with a supersonic core) that subsequently propagates upstream. In this (second) case, the isolator serves to confine this oblique shock-train, preventing it from propagating further and affecting the intake flow.

If the combustion-induced pressure rise is too large for the shock structure in the isolator to adapt to, or if no isolator is present, the shock-train (normal or oblique) will propagate further upstream, leading to inlet unstart [1]. Unstart, defined as the upstream displacement or “disgorging” of the original inlet shock system, is highly undesirable. The resulting flow spillage reduces the engine performance; moreover, the detached shock that forms can be highly unsteady, generating violent loads on the vehicle [3]. Therefore, an understanding of the fluid-combustion phenomena responsible for the formation of the shock structures that can lead to unstart is crucial for the reliable operation and robust design of scramjet-powered vehicles.

1.1. The role of LES for scramjets

Predictive simulations have a large role to play in the development of scramjet technology. At flight conditions, the effective free-stream stagnation pressure can be of the order of tens of MPa and the stagnation temperature well in excess of 1000 K. Realistic ground-testing at such conditions is extremely challenging, and all approaches lead to some form of limitation. Pre-heating the incoming flow using vitiation- or arc-heating provides long test times, but also introduces unwanted constituents in the oxidizer flow (see Ref. [3], p. 535). In general, this modified chemical composition will aid the ability of the fuel to ignite and burn, thus not representing the flight conditions exactly. Shock tunnels and expansion tunnels provide clean incoming air, but typically have test times limited to a few milliseconds.

Although steady-state simulation methods (most obviously, RANS) may often yield sufficiently accurate predictions for design and assessment at steady operating conditions, it is well known that these methods are less trustworthy in the presence of large-scale unsteady and/or separated flow. The large eddy simulation (LES) technique is generally more accurate for such flows, and also typically provides more accurate predictions of the turbulent mixing process. LES can therefore be expected to yield more accurate and trustworthy predictions than RANS (cf. Fulton et al. [6] for a direct comparison using a relevant scramjet flow). The major problem is that standard LES would require a completely infeasible computational cost if applied to a scramjet engine. The only feasible approach is to use LES with a wall-model, where the innermost 10–20% of the boundary layer is modeled; this reduces the computational cost by approximately three orders of magnitude for the combustor studied in the present work, for example.

A summary of the current state-of-the-art and different approaches in LES of scramjet flows is provided by Fureby [7].

1.2. The HyShot II scramjet

The HyShot II flight experiment was launched in 2002, successfully demonstrating supersonic combustion over a range of altitudes [8]. It was later the subject of multiple experimental investigations in the High Enthalphy shock tunnel Göttingen (HEG) of the German Aerospace Center (DLR) [9–15]. The flow in the HyShot II combustor has been studied computationally by at least three different groups. Karl et al. [16–20] performed a comprehensive RANS investigation of the full experimental set-up in the HEG shock tunnel, including the flow in the shock tunnel nozzle, the flow over the HyShot II forebody, and the reacting flow in the combustor. One outcome of this work was to show that the flow over the forebody can be accurately modeled as two-dimensional, a fact which is used in the present study. The chemically reacting flow was modeled Karl et al. by solving transport equations for the 9 species (H_2, O_2, N_2, H_2O, H, O, OH, HO_2, H_2O_2) considered in the chemical mechanism. The main challenge in this approach is the closure of the chemical source terms; this was done by a presumed probability density function (PDF) approach, with both δ- and β-PDFs considered. While the latter was found to produce a pressure profile that agreed slightly better with the experimental one, the difference was found to be small.

Pecnik et al. [21] extended the classic flamelet-based modeling approach to the supersonic regime, and applied this model to the HyShot II combustor within a RANS framework. One important contribution of Pecnik et al. [21] was to assess the importance of the spanwise domain size on the RANS results. Specifically, they compared cases covering 1/2 and 1/8 of the combustor width using the appropriate symmetry boundary conditions, and showed that the differences in the results were small. This finding will be used in the present study to model only a single injector in the LES, i.e., 1/4 of the full width.

Fureby et al. [22] and later Chapuis et al. [23] simulated the HyShot II combustor flow using LES. They solved transport equations for 7 species with a partially stirred reactor model to account for the unresolved chemical reaction fronts. In the earlier work [22] only half of the combustor width was modelled, with a symmetry boundary condition along the centerline. In the follow-on work [23], the full width of the combustor was included in the computation, using a grid of 51 M cells.

We note that the reactive flow in the HyShot II combustor is primarily mixing-controlled under the conditions considered here, with the possible exception of the flame-anchoring near the fuel injector. Berglund and Fureby [24] estimated a Damköhler number of ~ 40 in a (different) scramjet combustor with cold (340 K) incoming air. The incoming air in the present case is at 1300 K which leads to correspondingly faster chemistry. When using the present LES results to estimate a turbulent time scale representative of the combustor, we arrive at a Damköhler number of order $\mathcal{O}(100)$. Therefore, a flamelet-based combustion model seems justified. More importantly, in a mixing-controlled flow, details of the combustion model have less influence on the solution. The relative agreement between the computed pressure profiles by Karl et al. [19] and Pecnik et al. [21] (two studies which used very different turbulent combustion models) is consistent with this.

1.3. Objectives

The aim of the present study is twofold. First, we assess the ability of a wall-modeled LES method with a flamelet-based combustion model to accurately predict the flow in the HyShot II scramjet combustor at a manageable computational cost. Simulations are compared to earlier experimental data from HEG. Second, we apply this LES methodology to cases at higher equivalence ratios, both to predict the critical equivalence ratio at which unstart-like phenomena are first observed in the HyShot II combustor and to study and characterize the flow at these conditions. The predictions are compared with experiments carried out for the same purpose in HEG, described in the companion paper [15].

2. Methodology

2.1. LES methodology

The filtered compressible Navier–Stokes equations are solved for the conserved variables. The total energy E is defined as the