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Investigation on supersonic combustion of hydrogen with variation of combustor inlet conditions

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ABSTRACT

The present work numerically investigated the effect of variation in the inlet Mach number and stagnation temperature on the mixing of fuel with the oxidizer and the subsequent stabilization of a flame in a combustor at supersonic conditions. Dimensions of the studied combustor were taken from literature. It had a 10° wedge located at the top wall of the combustor. The combustor was modeled and analyzed using ANSYS FLUENT software. Three-dimensional, compressible, reacting flow calculations with a detailed chemistry model were performed. Turbulence was modeled using SST k-ω model. Necessary grid refinement was done to capture the incident oblique shock formed at the 10° wedge. Hydrogen was injected through the fuel inlet port. The computations were performed for Mach numbers of 2.0, 2.5 and 3.0 at the combustor inlet for a combustion inlet stagnation temperature of 1500 K. Later, the combustor inlet Mach number was kept constant at 2.5 and the combustor inlet stagnation temperature was varied as follows: 1500 K, 1700 K, and 1900 K. The results indicated that as the combustor inlet Mach number increased, the location of incidence of the oblique shock shifted to the downstream of the fuel inlet and it resulted in the better mixing of the fuel with cross flow stream of air and led to better degree of combustion of hydrogen. The contours of mole fraction of OH radical and hydrogen also corroborated the improvement in the mixing of fuel with the cross flow air and the subsequent flame stabilization at higher Mach numbers. The flow pattern, mixing of fuel with air and flame stabilization was not affected significantly till 1700 K whereas for 1900 K, combustion of hydrogen was more uniform.

Introduction

Hypersonic air breathing propulsion systems have a significant role in both the military and civilian applications. A significant amount of high-speed combustion research has been directed towards the design of the scramjet combustor due to emerging interest in hypersonic flights. The combustion and mixing timescales in a supersonic combustion are of the order of few milliseconds [1–3]. Hence, the duration

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available for complete combustion is very short. The intake air conditions drastically change with altitudes and for a ramjet flying in a flight regime of Mach number (Ma) 6–8; the combustor inlet Ma is expected to be in the range of 2–3 [1]. Therefore, it is important to study the effect of variation in the inlet Mach number on the mixing of fuel with air and subsequent combustion process in this flight regime.

To overcome the inherent problem of fuel-oxidizer mixing, variety of fuel injection strategies and flame holding methods had been proposed by earlier studies. The injection strategy in a supersonic combustor aims to increase the surface contact between the fuel and air and thus promote better mixing [4,5]. Also, different fuel injector geometries such as circular, elliptic and rectangular [6,7] had been tried and tested in supersonic combustors to enhance the mixing of fuel and air. The various fuel injection strategies that had been studied are transverse injection [6,8,9], angled injection [10] and parallel injection [11,12] of fuel into the air. Transverse injection of fuel results in a strong bow shock. It leads to boundary layer separation. It also results in a larger stagnation pressure drop across the combustor. For parallel high speed streams, improved techniques for mixing enhancement were required due to their limited mixing capabilities. This can be obtained either by shock waves [13,14] or by creation of stream wise vortices [15,16]. Ali et al. [13] numerically studied the interaction between the oblique shock wave and the transversal fuel injection and its effect on the fuel-air mixing and subsequent combustion. Their inlet conditions were: Ma = 2.5 and stagnation pressure = 0.5 MPa. Their results suggested that the mixing of hydrogen with air occurs at a lower rate in the absence of an oblique shock. They introduced a wedge and generated an oblique shock. The oblique shock increased the length of recirculation zone and augmented the mixing of hydrogen and air significantly. Mai et al. [17] studied the interaction between the incident shock wave and the transversal fuel jet flow and its effect on fuel-air mixing and combustion using NO-PLIF and PIV measurements. They performed measurements for the following inlet conditions: Mach number = 2.5, stagnation pressure = 0.5 MPa, stagnation temperature = 567–756 K. They concluded that the effect of the oblique shock when introduced downstream of injection slot results in expansion of recirculation region in comparison with no oblique shock. This enhanced mixing was due to the increase in the residence time of fuel with the oxidizer. Nakamura et al. [18] numerically investigated the transverse injection of hydrogen fuel into the cross flow stream of air in the presence of an incident shock wave. Their study showed that the incident shock wave at the downstream of the fuel injection slot acted as a flame holder even at lower air stream stagnation temperatures.

Apart from the challenge of mixing of fuel with air, flame holding and flame stability are also equally important for sustained supersonic combustion. Flame holding in supersonic combustor has been achieved using struts [7,11,19,20], pylon [21], ramp [22], backward facing step [23], cavity [4,5,8,24,25] or combinations of abovementioned methods [23,25]. It is widely reported that flame holding using cavity has provided better sustained combustion and minimal stagnation pressure losses [4,5,8,24,25]. Wang et al. [26] investigated the combustion characteristics in a supersonic combustor with a cavity where the hydrogen was injected upstream of cavity. It was found that stable combustion could not be obtained without a cavity. Jeong et al. [10] studied the influence of variation of stagnation enthalpies on the combustion in a cavity based combustor. They varied the combustor inlet stagnation pressure from 92 to 11 kPa, temperature from 899 to 1700 K, enthalpy from 3.82 to 6.45 MJ/kg and Mach number from 3.7 to 4. Their study concluded that the ignition delay time increased with decrease of total enthalpy and a combination of low total enthalpy and high equivalence ratio led to thermal choking. The angled injection upstream of the cavity allows the cavity to act as a flame holder. Strut based fuel injection scheme injects the fuel into the core of the supersonic flow stream and enhances mixing and combustion efficiency. Kumar et al. [11] performed the optimization of fuel injection struts for maximizing the combustion efficiency and augmenting the thrust. Their combustor inlet Mach number was 2.0. Their combustor inlet stagnation temperature and pressure were 1700 K and 3.91 bar. Kuang et al. [16] investigated the mixing of fuel with air by measuring the fuel distribution using PLIF technique at Mach numbers of 2 and 3. They studied the effects of wedge angle, strut length and shape of base of strut on the mixing of fuel and air. They found that struts with larger wedge angle and shorter root length showed better mixing performance. Grady et al. [25] numerically and experimentally studied the supersonic air flow over a ramped wall cavity with an upstream strut at an inlet Mach 2. Based on their measurement and numerical results, they reported that the inclusion of an upstream strut increased cavity recirculation and promoted mixing of fuel with air.

Three-dimensional numerical simulations of the supersonic hydrogen combustion in a model combustor were performed by Kumaran and Babu [23]. Hydrogen fuel was injected from the strut as well as wall injection ports into the air. Three injection schemes, namely, strut, staged (i.e., strut and wall) and wall were studied in this work. Their inlet operating conditions were: Mach number = 2.5, stagnation temperature = 1500 K and stagnation pressure = 1 MPa. They reported that the SST k-ω model predicted the mixing of fuel with air and flow separation phenomenon better than the Spalart-Allmaras turbulence model. Kumaran and Babu [27] studied the effect of single and multi-step reaction chemistry models. Their study showed that the detailed chemistry model predicted the reacting flow pattern better than single step chemistry. They used laminar finite rate model to model the combustion. They also mentioned that the single step chemistry model was capable enough to predict the overall performance parameters of the combustor with less computational cost than comparing to detailed chemistry model.

Based on the existing literature, it is very clear that the presence of incident shock enhances mixing and improves flame stability. Also, the detailed chemistry model predicted the reacting flow much better than the single step reaction chemistry. To the best of the author's knowledge, most of the existing numerical studies available on supersonic combustor were for specific inlet conditions only. Hence, it is important to analyze the effects of variation of the combustor inlet conditions on the mixing pattern and combustion efficiency. The objective of the present work is to investigate the