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Effects of self-throttling on combustion enhancement in supersonic flow with transverse injection

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ARTICLE INFO

Article history:
Received 17 December 2014
Received in revised form
14 April 2015
Accepted 18 April 2015
Available online 13 May 2015

Keywords:
Supersonic combustion
Shock and combustion interactions
Transverse injection
Compressibility modification

ABSTRACT

Efficient fuel/air mixing and combustion are difficult to achieve in supersonic flows. Transverse fuel injection from combustor walls is commonly used in Scramjet (supersonic combustion ramjet) design. The present study proposes an approach to enhance supersonic combustion under those conditions. Based on the specific jet-to-crossflow flow structures, it is proposed to connect the upstream region and downstream region of fuel injection slot through a channel. The higher pressure upstream of the slot drives part of the fluid flow into downstream regions and a self-throttling is established. Numerical method is used to validate the concept for a model combustor applying RANS (Reynolds-Averaged Navier–Stokes) approach. A compressibility modification $k-\varepsilon$ turbulence model is used which combines the dilatational compressibility effect and shock unsteadiness effect. The modified turbulence model is found to be able to capture the complex flow structures with good accuracy. Five operating conditions of jet-to-crossflow pressure ratio are studied for both nonreactive and reactive flows. The results show that the self-throttling changes the flow fields a lot, and affects the separation region and interactions of the reflection shock with mixing layers downstream the injection slot. Its effects on mixing and combustion efficiency are analysed for five different cases. The results demonstrate that self-throttling approach can increase the combustion efficiency with relative low injection pressure where the reflection shock goes downstream the injection slot. At the same time, more total pressure loss is observed. The combustion enhancement is more significant with relative low injection pressure. The self-throttling method has potentials for further studies.
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Introduction

Scramjet (Supersonic combustion ramjet) engine is under active consideration for propelling future hypersonic vehicles. However, the development of Scramjet encounters many challenges in achieving high combustion efficiency and good flame stabilisation accompanying with as low a total pressure loss as possible. From fuel point of view, hydrogen has strong advantages to other hydrocarbon fuels in terms of its high

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http://dx.doi.org/10.1016/j.ijhydene.2015.04.093
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reactivity, i.e. it gives the highest heat release with the shortest kinetic time. It thus has been used in many relevant studies of Scramjet [1–7]. Since the flow in the combustor is supersonic, the residence time of the air in a Scramjet engine is on the order of a millisecond for typical flight condition. Within this extremely short time, the fuel has to be mixed with the air and burned efficiently in order to obtain desired combustion efficiency. Additionally, the mixing process of fuel and air is depressed from inherent low mixing rates resulting from the compressibility effects in high speed flows [8,9]. Therefore, it is of crucial importance to obtain efficient mixing and combustion for the successful Scramjet design.

Several methods exist for injecting fuel into a Scramjet combustor. They can be generally categorised into two main categories [10]: the wall injectors [3,11,12] where fuel is injected through the wall of the combustor, and the strut injectors [13,14] that are located at the center of combustor where fuel is directly injected into the air stream. The wall injectors have the advantages of being easy to control the system and cause no loss in total pressure in case of no fuel injection. The transverse fuel injection into a combustor appears to be the simplest one and has been used in several Scramjet engine programs such as Hyshot Scramjet engine [15,16].

Interactions of supersonic main flow with transverse fuel injection have been the subject of many studies both experimentally and numerically [17–22]. Complex phenomena exist between the interactions of supersonic main flow and the transverse injected fuel (see Fig. 1(a)). The fuel jet becomes an obstruction of the mainstream, resulting in an arc shock upstream of the slot which consequently leads to large flow separations upstream of the slot. A low pressure region appears downstream the slot induced by fuel jet that establishes a balance with the surrounding flow through the compression shock. Deep fuel penetration and good mixing are found to be difficult in high Mach flows [17,18,21]. Downstream the injection slot, fuels gather in a narrow region near the wall that may result in poor combustion performance. To improve it, some methods have been proposed. The use of a cavity after the injector is a potential one and has been extensively investigated [23,24]. It was found that the cavity can improve the combustion efficiency significantly and also enhance the flame-holding. However, in the Scramjet engine startup stage, the low chamber pressure and unsettled fuel-air mixing could blow off the flame, even if a cavity is employed. It was proposed that the problem may be circumvented by modulating flow structures through air throttling [25,26], where the experiments show that successful ignition and flame-holding can only be achieved with the aid of air throttling in the experimental flow conditions.

By attentive studies on the typical flow structures of the supersonic flow with transverse injection (see Fig. 1(a)), it can be observed that there exist big wall pressure differences between the upstream and downstream regions of the injection slot. The pressure difference is as large as 3 times of the freestream pressure (see Fig. 1(b)). Experimental results of typical wall pressure distributions [17] lend strong support to the observation. The specific flow structures motivate the authors to explore a possible approach to enhance the combustion relating to air-throttling. It is proposed here to set up a channel which can connect the upstream and downstream regions of the injection slot. The fluid upstream with higher pressure then partly flows into downstream regions, which would improve the poor situation of fuel gathering near the wall.

In the present study, numerical methods are applied to validate the proposed approach for a model combustor. Both nonreactive and combustion flow fields are investigated. The self-throttling effects on the fuel/air mixing and combustion performance are explored for five cases, where the fuel injection pressures are varying which has been found to have big impact on the combustion mode in the Scramjet engine [24].

Numerical methods

Two-dimensional Favre-averaged Navier–Stokes equations for turbulent reactive flow with N species have been implemented in the present simulations. For the supersonic turbulent combustion problem considered, some specific concerns should be drawn such as turbulence modelling and chemical reaction mechanism.

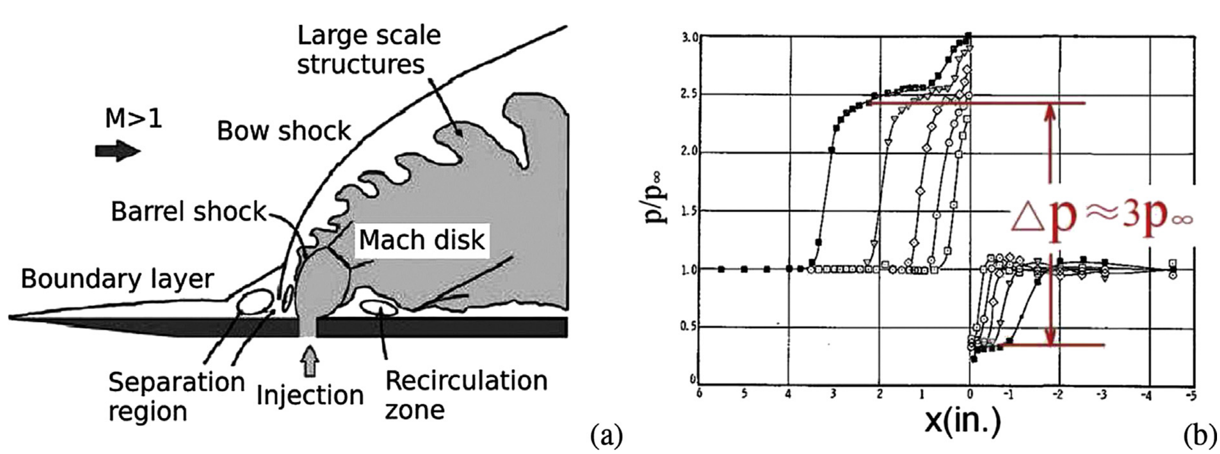

Fig. 1 – Interactions of supersonic flow with transverse injection: (a) main flow structures; (b) typical wall pressure distributions from experimental study [17].

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