Aerospace Science and Technology 77 (2018) 83–91

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Combustion stabilizations in a liquid kerosene fueled supersonic combustor equipped with an integrated pilot strut

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ARTICLE INFO

Article history:
Received 26 January 2018
Accepted 26 February 2018
Available online 1 March 2018

Keywords:
Pilot strut
Pilot flame
Combustion characteristics
Liquid kerosene

ABSTRACT

The numerical and experimental investigations have been conducted to test a newly designed integrated pilot strut. The integrated pilot strut consists of two neighboring small strut with shallow cavities, with the help of which, the fuel injection and flame holding are achieved in the supersonic combustor. The flowing characteristics in the internal flow duct of the pilot strut are evaluated with the numerical simulation method, results proving that a lower speed zone generates in the internal flow duct in the supersonic combustor and the local equivalence ratio in the low speed zone is suitable for combustion. Then, a series of experiments have been conducted in the flight condition of $Ma = 5$, with stagnation state $T_t = 1270$ K, $P_t = 1.20$ MPa. Experimental results show that a pilot flame generates in the internal flow duct of the pilot strut, based on which, the main fuel injected from the sidewall of the strut is ignited, and the global flame is established in the whole combustor. The combustion of the main fuel leads to a thermal chocking at the exit of the strut. Further, the thermal chocking is beneficial to the self-stabilization of the pilot flame. With the combustion organization strategy of the pilot strut flame holding, the global flame is stabilized in a wide range of equivalence ratio changing from 0.15 to 0.75 in the supersonic combustor, and the combustion characteristics in different equivalence ratios are analyzed in this paper. The integrated combustion organization approach by the pilot strut with internal cavities is demonstrated feasible and a high combustion performance is obtained.

1. Introduction

Scramjet is regarded as one of the most efficient air-breathing propulsion devices in supersonic flight condition for the advantages of high impulse and high speed [1,2]. One of the main challenges in the scramjet is the flame stabilization in the supersonic combustor. The fuel resident time in the supersonic combustor is of the order of microsecond, which makes it difficult to achieve an efficient mixture process between fuel and the oxidant. Due to the ability in wall cooling in the combustor, the liquid kerosene is widely used as the propellant in the supersonic combustor [3,4]. But the liquid kerosene should be well atomized and mixed before ignited, and the ignition delay time of the liquid kerosene is also longer than that of the gaseous fuel, which makes it more difficult to achieve the efficient combustion in the liquid kerosene fueled supersonic combustor. Under these circumstances, an efficient flame holder is needed to maintain a stable operation of the combustor over a broad range of flow conditions with less extra losses.

The basic principles of the flame stabilization in the supersonic combustor is to build a low speed zone to increase the resident time of the fuel. The most popular flame holders used in the supersonic flowing could be divided into two kinds, including the non-intrusive method and the intrusive method. In the non-intrusive method, a wall mounted cavity [5–8] or a rearward facing step [9,10] could help to generate a low-speed recirculation zone near the wall, in which zone the fuel would be mixed with the air. In this non-intrusive flame holding combustor, the initial flame is established in the recirculation zone located in the side wall of the combustor, then it propagates to the main flow to improve the combustion performance. The main flame mainly gathers closely to the wall of the combustor, leading to an addition problem for wall thermal protection, which makes it difficult for the long time working of the combustor.

Different from the combustion characteristics in the non-intrusive method, the combustion is stabilized in the center of the main flowing in the intrusive method. In the intrusive method, a strut is equipped in the center of the main flow [11,12]. The

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https://doi.org/10.1016/j.ast.2018.02.035
1270-9638/

Nomenclature

Ma	Mach number	
p_w	Wall static pressure	MPa
P_t	Total pressure	MPa
T_t	Total temperature	K

Abbreviations

ER	Equivalence Ratio
PJ torch	Plasma Jet torch
Experiment	Expt.

flame generates in the center of the main flow and propagates to the combustor wall, and the flame and the combustor wall will be separated by the high speed flowing, which is beneficial to the wall thermal protection. With the effect of the strut, a low-speed recirculation zone is formed at the strut back, and a shear layer zone is also formed in the tailing edge of the strut. The initial flame is firstly established in the recirculation zone and the shear layer zone, then it propagates to the main flow. While, the ability of the strut in the flame holding is associated with the width of it [13]. When the width of the strut is less than 7 mm, the combustion is impossible to be established. It is better to design the strut with the width of larger than 10 mm to ensure the flame stabilization in the supersonic flowing when taking hydrogen as the fuel. In the liquid-kerosene fueled combustor, the width should be larger, which would be unbeneficial to the combustor drag reduction. However, if the thickness of the strut is too large, it will result in a large total pressure loss, which will reduce the performance of the combustor. Usually, in the strut-equipped supersonic combustor, some other wall mounted flame holders are also adopted to enhance the combustion performance, such as strut-cavity combined flame holder [14–16]. In this combustion stabilization strategy, the strut mainly plays the roles of fuel injection rather than flame stabilization. Some other methods are put up to achieve the flame stabilization with a thin strut. An oxygen-pilot strut with the front blockage of 6% is designed by Hu [17]. The strut is equipped in a flush wall supersonic combustor, and the stable combustion is achieved in a wide range of equivalence ratio without any other wall mounted flame holder [18,19]. The flame propagation process [20] and the flame stabilization mechanism [21] are investigated in the supersonic incoming flow based on the thin strut. Then, the oxygen-pilot strut is widely used as the flame holder in different combustors [22–26]. Results of the investigations prove the ability of the strut in the flame stabilization. While, in the thin strut flame-holding method, some oxygen is injected into the combustor through the injector in the strut back, which is prerequisite to the flame stabilization. Results [18] indicates that the oxygen plays an important role in the flame stabilization. Without the supply of the oxygen, it is impossible to achieve flame stabilization by using such a thin flame holder in the supersonic combustor. In practice, the addition oxygen supply could make the scramjet system more complex to maintain. In order to achieve a stable oxygen injection, the total weight of the scramjet would be higher, leading to a lower performance of the scramjet.

Both of the flame stabilization methods have their pros and cons. In the non-intrusive method, the low-speed recirculation zone is large enough to achieve an efficient flame stabilization. While, in the intrusive method, the fuel could be injected directly into the core flowing, leading to a higher combustion efficiency. In this paper, a new designed pilot strut was numerical and experimental tested in a liquid-kerosene fueled supersonic combustor, and the designed device could combine the advantages of both cavity and strut. The pilot strut consists of two neighboring small struts with shallow cavities on their opposite surfaces. Between the two neighboring small struts, a mini subsonic combustor is formed to achieve the flame stabilization. The pilot strut was equipped in the expansion part of the combustor, which was helpful for reducing the front blockage ratio to decrease the total pressure loss.

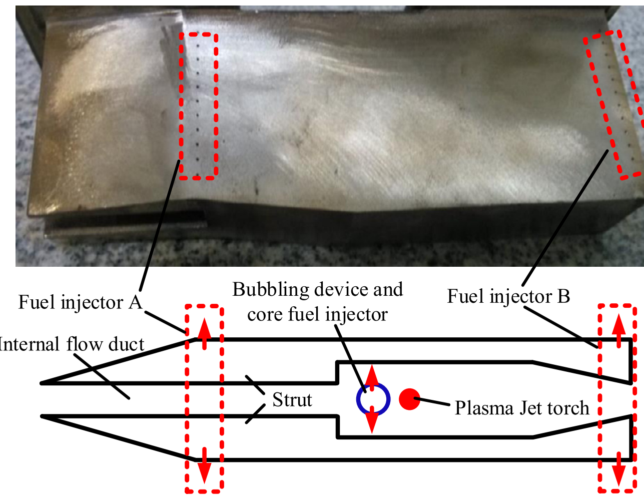

Fig. 1. Schematic diagram of the prototype of the integration pilot strut.

With the effect of the pilot strut, the flame is stabilized under the $Ma = 5$ flight condition in a wide equivalence ratio range from 0.15 to 0.75, and the combustion characteristics in different fuel injection strategies were analyzed.

2. Experimental setup and numerical simulation method

2.1. Test facility

A new fuel injection and flame holding integrated combustion organization approach by the combination of small struts and shallow cavity is presented to avoid the problems as the excessively high thermal load at the wall downstream of the cavity, large drag of thick strut, etc. The pilot flame will be established in the internal flow duct of the strut, and the main fuel injected into the combustor through the strut side wall will be ignited by the pilot flame to form the global flame. The schematic diagram of the pilot strut prototype is shown in Fig. 1.

As is shown in Fig. 1, a separate path for a small portion of the incoming airstream is formed between two neighboring small struts with shallow cavities on their opposite surfaces. The internal flow duct is a mini subsonic combustor, which could be divided into three part, namely the area-constant isolator, the mini combustor, and the contraction section. The profile of the combustor is like a couple of cavities equipped in the wall of the combustor, which could achieve flame holding in the mini subsonic combustor. There are three groups of fuel injection. The core fuel injector is located in the mini combustor, and in order to enhance the fuel atomization, a bubbling device is adopted. The schematic diagram of the bubbling device is shown in Fig. 2. The other two groups of fuel injectors are set in the leading edge and the tailing edge of the strut, named as fuel injector A and fuel injector B. The liquid kerosene injected from injector A and injector B is the main fuel with a higher equivalence ratio. In this paper, the core fuel is ignited by a Plasma Jet torch (PJ torch) equipped at the back of the bubbling device just like marked in Fig. 1.