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Local and global flame characteristics in a liquid kerosene fueled supersonic combustor equipped with a thin strut

Junlong Zhang [a], Juntao Chang [b,*], Jicheng Ma [a], Yuanshi Zhang [a], Wen Bao [a]

[a] School of Energy Science and Engineering, Harbin Institute of Technology, 150001 Heilongjiang, People's Republic of China
[b] Academy of Fundamental and Interdisciplinary Sciences, Harbin Institute of Technology, 150001 Heilongjiang, People's Republic of China

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ABSTRACT

The investigations of local and global flame characteristics in a liquid kerosene fueled supersonic combustor based on the strut flame holder were conducted. A thin strut with the thickness of 6 mm is equipped in the center of the main flow, and there are two rows of oxygen injectors at the tailing edge of it to enhance the combustion. The room-temperature liquid kerosene is chosen as the fuel in the flush wall combustor without any cavity and other flame holders. The experimental condition is at flight Mach number of 6, and the Mach number is 2.8 at the entrance of the combustor, with stagnation state $T_t = 1680$ K, $P_t = 1.87$ MPa. The flame images in different equivalence ratios and oxygen mass flow rates are well captured and reproduced by the high-speed camera. Experimental results show that the flame mode could be divided into two modes, namely, the local flame mode and the global flame mode. With the injection of the oxygen, a local oxygen enriched zone forms in the recirculation zone, and the local flame generates in this location. The transition process from local flame to global flame is influenced by the equivalence ratio and the oxygen mass flow rate. There are three flame stabilization patterns being found accompanied with the changing of the equivalence ratios, and different stabilization patterns correspond to different flame modes. The main function of the injected oxygen is to establish the local flame and to strength it, then the enhanced local flame will act as the pilot flame to ignite the extra fuel to form the global flame. In addition, the oxygen will improve the efficiency of the global combustion to a certain degree. All in all, these results are valuable for the optimization of the fuel and oxygen injection strategy.

1. Introduction

In the recent years, scramjet is widely investigated by researchers, and it is regarded as one of the most efficient air-breathing propulsion devices in supersonic flight condition [1,2]. Combustor is the key component of a scramjet, and some issues about fuel injection and flame holding in supersonic combustor need to be solved urgently. In the supersonic combustor, the residence time of fuel is only by an order of milliseconds, which makes it difficult to achieve an efficient mixture between the fuel and the main flow. In this condition, a flame holder is necessary to increase the residence time of the liquid fuel to achieve the flame holding, such as, strut [3], cavity [4–7], and air throttling [8,9], which have been studied by the researchers worldwide. The basic principle to achieve the supersonic combustion is to increase the residence time of the fuel, and a subsonic zone is also indispensable in the initial stage of the flame establishment process.

In the wall mounted flame holder condition, such as cavity and facing step, the igniter and the fuel/air mixing zone is located near the sidewall of the combustor, the combustion generating near the wall, causing the additional problems for combustor wall thermal protection. The core combustion method based on an intrusive fuel strut can solve the problem on wall heat protection to a certain degree. In the strut based supersonic combustor, the main combustion generates in the center of the main flow, and the flame is separated from the combustor wall, which is of great benefit to the combustor wall cooling and injection penetration depth of the fuel. Owing to the advantages, the strut is paid more attention on to achieve the stabilized combustion in the supersonic combustor. One of the main functions of the center strut is to inject the fuel into the main flow, and rapid mixing can be achieved at the sidewall of it [10–12]. The flow field structure and the mixing characteristics of the strut injectors were studied using color Schlieren and Mie scattering technique [13–15]. Some other measurement

* Corresponding author.
E-mail addresses: junlongzhang1990@163.com (J. Zhang), changjuntao@hit.edu.cn (J. Chang), 15B902032@hit.edu.cn (J. Ma), zhangyuanshi58@163.com (Y. Zhang), baowen@hit.edu.cn (W. Bao).

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Nomenclature

Ma	Mach number	
p_w	Wall static pressure	MPa
P_t	Total pressure	MPa
T_t	Total temperature	K
m_{o2}	Mass flow of the oxygen	g/s

Abbreviation

ER	Equivalence Ratio
PJ torch	Plasma Jet torch

methods were also used in the flame behavior studies in transition regimes, such as Schlieren technique and "laser knife", which was successfully used for resolving complex transient flow structures by Smirnov [16,17]. Tian [18–21] did lots of studies on the flame characteristics in a cavity-mounted supersonic combustor with the method of high speed color flame emission images and numerical simulation, and the flame stabilization mode and flame propagation characteristics were made known. The numerical simulation is also a good method to evaluate the mixing behavior in detail. Numerical simulation was carried out to investigate the influence of different injection positions for single and multiple injectors on mixing efficiency of fuel in supersonic combustor with staggered rear strut and cavity [22], proving that the injector which facing directly to the declivity of the strut has better effect on spreading of fuel and mixing efficiency.

In addition to the effect of enhancing mixing, the strut is also used as the flame holder coordinating with other flame holders. Zhu [23] did some studies on flame stabilization in supersonic combustor with the staged-strut injector taking liquid kerosene as the fuel. Two strut injectors were installed perpendicularly in the combustor to get the stabilization combustion, and a cavity flame holder was equipped in the wall at the downstream of the struts. A cavity-strut combustor in the supersonic flow was studied by Hsu [24], and three different struts with fuel injectors were mounted near the cavity leading edge to study flame propagation and ignition of fuel in the core flow region. Some large eddy simulation [25] was carried out to get the flow characteristics in detail based on the strut-cavity combustor, and results showed that the multiple shear layers in the wake of the strut provided a wider mixing region that had the potential for flame stabilization. The functions of fuel mixing and combustion enhancement of the strut was proved by the numerical simulation [26]. Huang [27,28] did some investigations on the ram–scram transition mechanism in a strut-based dual-mode scramjet combustor, evaluating the influences of the inlet boundary conditions at the entrance of the isolator, the injection strategy, and the jet-to-crossflow pressure ratio on the mode transition in detail. The strut configurations and locations had also been optimized in accordance with the combustion performance [29,30].

However, most of the experimental and numerical studies based on the strut take gaseous fuel as propellant, such as hydrogen and ethylene [31–34]. It is more difficult to achieve ignition and stabilization combustion for liquid kerosene due to the physical properties of it. The liquid kerosene should be well atomized and blended before ignited [35], and the ignition delay time of the liquid kerosene is longer than that of the gaseous fuel. All these disadvantages of the liquid kerosene make the combustion ignition and stabilization more difficult in the strut based combustor.

In the above mentioned studies about the strut, the main function of the strut is to inject fuel into the combustor. Even if the strut is used as the flame holder, it is usually coordinated with other flame holders, such as, cavity and air throttling. In these conditions, the strut is designed thickly, leading to a large total pressure loss. In this paper, a thin strut is equipped in the center of a flush wall scramjet combustor, acting as the flame holder. In order to achieve ignition and flame stabilization, a certain amount of oxygen is injected into the recirculation zone. In the previous studies, the O_2 pilot strut was investigated in the supersonic combustor [36–38], proving its ability in the flame holding, and it was widely used as the flame holder in different combustor [39–43]. Experimental studies found that the injected oxygen played a very important role in the combustion process. In the lower equivalence ratio and lower oxygen mass flow rate conditions, there is no pressure rising in the combustor, but a local flame generates at the strut back. In this paper, some investigations have been conducted to study the local and global flame characteristics based on strut flame holder. The flame images are captured and reproduced by the high-speed digital camera in different equivalence ratios and different oxygen mass flow rates. At the same time, the pressure distributions in the combustor are detected by the pressure sensors equipped in the side wall of the combustor. With the investigations in this paper, the local and global flame characteristics are discussed, and the flame stabilization mechanism of the oxygen pilot strut has been brought to light.

2. Experimental setup

2.1. Test facility

The experiments in this study are conducted on a ground directed test rig, and an air vitiation heater is used to simulate the supersonic incoming air flow. Ethanol and oxygen are burned in the combustor of the heater, producing the high enthalpy inflow. Then the high enthalpy air flow is accelerated to $Ma = 2.8$ through a Laval nozzle. The model combustor is connected to the outlet of the Laval nozzle. The main dimensions of the experiment combustor model are shown in Fig. 1. A strut is equipped in the center of the air flow, and the strut back is aligned with the exit of the isolator. In order to record flame images in the strut back, a quartz window is equipped in the upper wall of the combustor, and the location of the window is shown in Fig. 1. The camera field of view is 90×52 mm, and the resolution ratio of the pictures is 800×512 pixels. A high speed camera is used to record the flame images.

In the experiments, the main function of the strut is fuel injecting and flame holding. The thickness of the strut is 6 mm with the front blockage of 6%. The total length of the strut is 54 mm, with a wedge angle of 15°. There are two rows of the injectors, marked with A and B in Fig. 2. The A injector marked with the red line is the fuel injector. The direction of the fuel injection is normal to the leading edge of the strut. The oxygen injector is at the tailing edge of the strut. With the help of the oxygen, the combustion is established and enhanced. The fuel is ignited by a Plasma Jet torch (PJ torch) mounted at the strut back, and the power of the PJ torch in the stable working status is about 1.1 kW. The function of the PJ torch is to provide the energy of the flame establishment progress, and some oxidizing substances will also be produced by the Plasma Jet torch, which is beneficial to the combustion. Some pressure sensors are installed in the center line of the side wall to monitor the pressure data.