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Effects of fuel cracking on combustion characteristics of a supersonic model combustor

Zhan Zhong*, Zhenguo Wang, Mingbo Sun

Science and Technology on Scramjet Laboratory, National University of Defense Technology, Changsha 410073, China

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ABSTRACT

The compositions of endothermic hydrocarbon fuels in cooling channels of regenerative cooled scramjet engines change along with fuel cracking. To investigate the effect of fuel compositions variation resulting from cracking on the combustion characteristics of supersonic combustors, a series of combustion tests with a wide range of equivalence ratios were conducted in a direct-connected test rig under the inflow conditions of $Ma=3.46$ and $T_t=1430$ K. The combustion characteristics of room temperature ethylene and vaporized China no. 3 aviation kerosene (RP-3) with negligible cracking were analyzed and compared based on the measured static pressure distributions along the combustor wall, fuel specific impulses, flame luminosity images and the one-dimensional average flow parameter distributions calculated by a quasi-one-dimensional data analysis method. The experimental results showed that the differences between the combustion characteristics of vaporized RP-3 and ethylene were sensitive to equivalence ratio. Under low equivalence ratios, vaporized RP-3 and ethylene had remarkably different combustion characteristics. Ethylene had an obvious higher static pressure level, specific impulse and combustion efficiency than vaporized RP-3 for its higher activity. The difference of combustion performance between vaporized RP-3 and ethylene was narrowed with the increase of equivalence ratio and the corresponding combustion condition improvement. When the equivalence ratio increased to 1.09, vaporized RP-3 and ethylene had tiny difference in combustion performance.

1. Introduction

Aircraft operating at hypersonic speeds is confronted with severe cooling problems on the airframe and engine components. In practical hydrocarbon-fueled scramjet [1,2] and pulsed detonation engine [3,4], regenerative fuel cooling is a commonly adopted method [5–9]. In this case, the onboard fuel flows through the cooling channels to absorb a part of heat imposed by the combustion and flight environment before being injected into the combustor. Hence, the fuel temperature and property vary with flight stages [10]. In the cooling channels, fuel state could transfer from initial liquid to gaseous, supercritical or cracked, altering fuel compositions and properties accordingly.

The changes in fuel phases and compositions will affect the subsequent injection behavior, fuel-air mixing, ignition and combustion characteristics in combustors [11]. Gao et al. [12] studied the injection of supercritical RP-3 into a quiescent atmospheric environment using schlieren imaging technique. The results showed that supercritical kerosene jets injected above the critical point undergo ideal-gas-like expansion and exhibit visible Mach disk shock structures. Fan et al. [13–16] and Yu et al. [17–19]compared the combustion efficiency of supercritical and cracked kerosene with that of liquid

* Corresponding author. Tel.: +86 13755011408.
E-mail address: zhongzhan_nudt@163.com (Z. Zhong).

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Nomenclature

Ma	Mach number
T_t	stagnation temperature of vitiated air
P_t	stagnation pressure of vitiated air
Φ	fuel-air equivalence ratio
Y_i	mole fraction of species i
ΔF	thrust increment
I_s	specific impulse of fuel
$\dot{m}_f$	mass flow rate of fuel

kerosene. The results indicated that supercritical kerosene has remarkably higher combustion efficiency than liquid kerosene. This is caused by the injection, atomization and evaporation difference between the supercritical fuel and liquid fuel. The supercritical fuel can be directly transformed to the gaseous state without atomization and evaporation after injection; In contrast, extra induction time is needed for the liquid fuel to accomplish the atomization and phase transition process. Moreover, the evaporation process of droplets is much complex in the scramjet combustor, which is a non-equilibrium process. Smirnov et al. [20–22] developed a mathematical model to study the non-equilibrium evaporation of droplets in sprays, combustible mixture formation and combustion simulation, and found that the lifetime for single evaporating droplet could be several times longer under non-equilibrium conditions as compared with equilibrium ones. The combustion efficiency is further improved by partial cracked kerosene, comparing to that of supercritical kerosene. Helfrich et al. [23] investigated key performance parameters of the pulsed detonation engine fueled with thermal and catalytic cracking of JP-8 experimentally. The results indicated that the cracked JP-8/air mixture produces a shorter ignition time, deflagration-to-detonation transition (DDT) time and DDT distance for the majority of equivalence ratio, as compared with flash-vaporized JP-8/air mixtures. The ignition and detonability limits are also expanded by cracked fuel.

The previous studies have demonstrated that the cracking of hydrocarbon fuel holds the potential to improve scramjet combustor performance. However, the cracking reactions and conversion rate of hydrocarbon fuel dramatically change with fuel temperature, residence time and cracking type [24–27] (e.g., thermal cracking or catalytic cracking). Consequently, the compositions and properties of cracked hydrocarbon fuel will vary with practical cracking conditions, which will affect the subsequent combustion process. In addition, the component of cracked hydrocarbon fuel is too complex to be accurately measured. The uncertain compositions of cracked hydrocarbon fuel make it hard to quantitatively analyze and repeat the combustion test results.

RP-3 and ethylene are both widely used hydrocarbon fuel in supersonic combustion tests. Ethylene is a preferred cracked product of RP-3, because this cracking reaction can both improve the cooling capacity [14] and chemical activity of RP-3.

In order to investigate the effect of fuel cracking on the combustion characteristics of supersonic combustors, ethylene is used as the surrogate fuel of fully cracked RP-3 and vaporized RP-3 whose cracking can be neglected with a temperature of approximately 780 K is used for comparison. RP-3 at 780 K could be injected like ideal gas [12], without going through the phase transition process. A series of combustion tests were conducted in a wide range of equivalence ratios using the aforementioned fuels. The differences of combustion characteristics between vaporized RP-3 and ethylene were systematically compared and discussed based on the measured wall static pressure distributions, fuel specific impulses and flame luminosity images. The impacts of hydrocarbon fuel cracking on the combustion process in supersonic combustors are also estimated.

2. Experimental description

2.1. Test facility

A direct-connected test facility was used in the experiments, as shown in Fig. 1. The facility is composed of a pedestal, an air heater, a scramjet model combustor, a fuel supply system, and a measure-control system. The entire test rig, including the air heater and the model combustor, is mounted upright on a platform.

The air heater which burns pure ethylalcohol and oxygen is used to heat the air from room temperature to about 1430 K and increases the total pressure of vitiated air up to 3.6 Mpa. The total mass flow rate of the vitiated air is 1.71 Kg/s. A two-dimensional converging-diverging $Ma = 3.46$ nozzle section, configured with a rectangular nozzle, was adopted to generate the designed inflow conditions. The detailed flow conditions for the nozzle are listed in Table 1. The repetitive ability of the experiment system has been validated by a large number of experiments [28,29].

The model combustor shown in Fig. 2 has a total length of 2200 mm and consists of one nearly constant area section of 674 mm and three divergent sections with expansion angles of 2.5°, 3.5°, and 4°, respectively. The entry cross section of the combustor is 54.5 mm in height and 75 mm in width.

As shown in Fig. 2, two integrated fuel-injection/flame-holder cavity modules of same size were installed on the combustor upper and bottom walls respectively. We denote the cavity installed on the upper/bottom wall as '*T1/B1*'. As shown in Fig. 3, the depth D, length L, width W and aft ramp angle A of each cavity are 15 mm, 110 mm, 75 mm and 45° respectively. Vaporized RP-3 and room temperature ethylene were both transversely injected at Mach 1 through two injectors mounted upstream of the two parallel cavities, which are denoted as 'injector *I1*' and 'injector *I2*' separately. Each injector has three orifices with 2.0 mm in diameter, and the distance from the injector centerline to the cavity front wall is 8 mm. Pilot hydrogen was transversely injected into the combustor through an orifice of 3.0 mm in diameter located upstream of injector *I1*. A forced spark ignition plug was mounted in cavity *T1* to ignite pilot hydrogen.

The pressures of the combustor along the centerline of the top wall were measured by a pressure scan system (Pressure