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Experimental investigation on combustion performance of cavity-strut injection of supercritical kerosene in supersonic model combustor

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A B S T R A C T

Supersonic combustion with cavity-strut injection of supercritical kerosene in a model scramjet engine was experimentally investigated in Mach 2.92 facility with the stagnation temperatures of approximately 1430 K. Static pressure distribution in the axial direction was determined using pressure transducers installed along the centerline of the model combustor top walls. High speed imaging camera was used to capture flame luminosity and combustion region distribution. Multi-cavities were used to and stabilize the combustion in the supersonic combustor. Intrusive injection by thin struts was used to enhance the fuel-air mixing. Supercritical kerosene at temperatures of approximately 780 K and various pressures was prepared using a heat exchanger driven by the hot gas from a pre-burner and injected at equivalence ratios of approximately 1.0. In the experiments, combustor performances with different strut injection schemes were investigated and compared to direct wall injection scheme based on the measured static pressure distributions, the specific thrust increments and the images obtained by high-speed imaging camera. The experimental results showed that the injection by thin struts could obtain an enhanced mixing in the field but could not acquire a steady flame when mixing field cannot well match cavity separation region. There is no significant difference on performance between different schemes since the unsteady intermittent and oscillating flame leads to no actual combustion efficiency improvement.

1. Introduction

In recent years, there has been considerable interest in hydrocarbon-fueled scramjet propulsion. In hydrocarbon-fueled scramjet operations, the onboard fuel will be also used as a coolant and its temperature and state will vary with the different flight stages. When both fuel temperature and pressure are higher than the thermodynamic critical point, the fuel becomes supercritical. Supercritical fuel exhibits liquid-like density and gas-like diffusivity. During injection the supercritical fuel can be directly transformed to the gaseous state without atomization and vaporization processes. Previous experimental investigation [1,2] demonstrated that the use of supercritical kerosene injection holds the potential of enhancing fuel-air mixing and promoting overall burning and in comparison with liquid fuel injections at similar fuel flow rates, the pressure rises in the combustor with supercritical fuel injections could be increased significantly at relatively lean conditions. However, further increase in the fuel flow rate and the pressure rise with the single-stage injection was limited by the upstream propagation of boundary layer separation due to excessive heat release. Thus, the advantage of supercritical fuel injection has not been fully accomplished with single-stage injection. The idea of staged fuel injection [3,4] utilizes the combustion of an upstream-injected fuel to improve the mixing and burning processes of the downstream-injected fuel, while still keep the fuel flow rate through the upstream injectors below the allowable value. In this case, better pressure distributions and higher thrust could be attained.

Cavity-based flameholders are commonly used in hydrocarbon-fueled scramjet combustors; however, detailed information concerning the behavior of these devices, their optimal shape and fueling strategies, combustion stability, interactions with disturbances in the main air flow (i.e., shock trains or shock-boundary layer interactions), and capability of ignition and sustained main combustion is largely unavailable in the existing literature. Studies [5,6] of cavity-based flameholders in supersonic flows conducted at AFRL/PRA have illustrated that the combustion around a flameholder can be optimized with proper fueling. Fuel injection in the scramjet combustor has been studied for decades, with the main emphasis being placed on mixing and efficient combustion. To achieve fueling in the supersonic core flow region, strut injectors have been used to improve fuel distribution and mixing in supersonic combustors [7–9].

The main objective of this study is to examine the coupling

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Nomenclature

Ma	Mach number
T**n**	the **n**th cavity on top wall of the scramjet combustor
B**n**	the **n**th cavity on bottom wall of the scramjet combustor
D	cavity depth
L	cavity length
LD	cavity length to depth ratio
A	cavity rear wall angle
ψ	equivalence ratio
T**n**(w)	wall injection set upstream of the cavity T**n**
B**n**(w)	wall injection set upstream of the cavity B**n**
T**n**(s**i**)	the **i**-th strut injection set upstream of the cavity T**n**
B**n**(s**i**)	the **i**-th strut injection set upstream of the cavity B**n**
T_{0i}	stagnation temperature of the supercritical kerosene
P_{0i}	stagnation pressure of the supercritical kerosene

between the cavity and the strut-injected fuel and the potential to improve the combustion performance in a scramjet engine. Conventional and advanced diagnostics are used to characterize the interactions between the cavity and the wake region created by struts.

2. Facility descriptions

A direct-connected test facility [10] was used for the experiments. The facility was composed of air heater, supersonic nozzle and scramjet combustor. The air heater burns pure ethylalcohol and oxygen continuously to heat air from room temperature up to 1430 K and increase the total pressure of vitiated air up to 2.0 Mpa. The total mass flow rate of vitiated air was 1.71 Kg/s. The two dimensional converging-diverging M = 2.92 nozzle section, configured with a rectangular nozzle, was adopted to develop the designed inflow conditions.

The model combustor shown in Fig. 1 had a total length of 2200 mm and consisted of one nearly constant area section of 610 mm and three divergent sections with the expansion angles of 2.5, 3.5, and 4 degrees, respectively. The entry cross section of the combustor was 54.5 mm in height and 75 mm in width. The detailed information about this model combustor can be found in our previous work [11–13].

There are three cavity installations in the test section, one in bottom wall and the other two in the top wall. Here for brevity we denote the cavity installed on top wall nearer to the isolator as 'T1', and the downstream cavity as 'T2'. The cavity on the bottom wall is denoted as 'B1'. In this paper, the cavity depth is denoted as D, cavity length to depth ratio as LD, the cavity aft wall angle as A, so D15LD7A45 represents a cavity with depth of 15 mm, length to depth ratio of 7, and aft wall angle of 45 degree; for all cavities the width is 75 mm. In the present tests, only D15LD7A45 cavity is used and T1, T2 and B1 have the same configuration. Fig. 1 also shows the scheme of the fuel injection location. Injection is conducted on a module which could be uninstalled. Gaseous hydrogen with room temperature is transversely injected into the combustor upstream of T1 cavity for kerosene ignition.

Two wall injector configurations (orifice number × diameter: 3 × Φ2.0 mm and 3 × Φ1.5 mm) were used in the experiment. Injection schemes were formed by changing different injector module upstream of the cavity. The distance from the injector centerline to the cavity front wall is 10 mm. Besides the wall injector T1, T2 and B1 were used, another injector denoted as B0 was used on the bottom wall. The B0 injector module with three orifices is installed 276 mm downstream of the isolator outlet.

The pressures of combustor along the centerline of the top wall in the test section are measured by a series of strain-gauge pressure transducers through taps with the diameter of 0.5 mm distributed on the top wall.

The struts used here contain two configurations, which are shown in Fig. 2. Strut #1 has a configuration with length 50 mm, thickness or width 7 mm and height 26 mm. The declined angle is 45°. Strut #1 has three orifices with 2 mm diameter on the afterbody transverse section. The distance of the orifices to the base wall is 10 mm, 16 mm, 22 mm respectively. Strut #2 has a configuration with length 50 mm, thickness 7 mm and height 34 mm. Strut #2 has four orifices with diameter = 2 mm on the left and right side face. The distance of the orifices to the base wall is 22.5 mm, 31.0 mm respectively. If the strut module is used, the wall injection module upstream of the cavity will be removed. The two struts are both designed to provide a direct intrusive injection and enhance the mixing of fuel the core airflow. Strut #1 is installed on the bottom wall and opposite to T1 cavity. Since the location is upstream of main combustion zone, strut #1 uses afterbody injection, which needs a mixing streamwise-length and avoids thermal choke caused by fast mixing and combustion in the upstream section. We have shown that fast combustion led to isolator unstart in the previous work [12]. Strut #2 is installed close to T2 or B1 cavity and expected to get a quick mixing and combustion in the downstream region. Strut #2 uses side-face injection and the injection orifices are located in the core flow to enlarge the adjacent interface with the core airflow and obtain an enhanced mixing. This work aims at high efficiency combustion with low pressure loss, therefore we chose the thin struts only for injection but not for flame stabilization.

The flowfield is visualized by high speed imaging camera, through the quartz window which is 190 mm × 100 mm for photograph camera. Images are recorded by high speed imaging camera. Although the camera could reach the speed of 120,000 fps when the image resolution is 128 × 64 pixels, only 4000 fps is

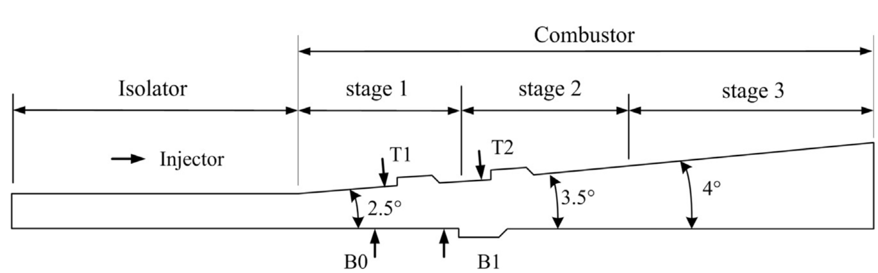

Fig. 1. Schematic of test section and cavity installation scheme.