

Combustion characteristics in a supersonic combustor with hydrogen injection upstream of cavity flameholder

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Abstract

Combustion characteristics in a supersonic combustor with hydrogen injection upstream of a cavity flameholder were investigated both experimentally and numerically. The combustion was observed to be stabilized in the cavity mode around the shear layer via a dynamic balance and then spread into the main stream in the region around the jet centerplane where the flow was decelerated and turned to the main stream, supplying a favorable condition for the combustion to spread. The combustion spreading from the cavity shear layer to the main stream seemed to be dominated not only by the traditional diffusion process but also by the convection process associated with the extended recirculation flows resulting from the heat release and the interaction between the jet and the cavity shear layer. Therefore, the cavity-stabilized combustion appeared to be a strongly coupled process of flow and heat release around the cavity flameholder.

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1. Introduction

Scramjet engine lets the air stream enter into the combustor supersonically and organizes combustion within supersonic flow, where robust flameholding schemes are necessary due to the short combustor residence time. One promising candidate for such a flameholder is the wall cavity which has been shown to be effective in stabilizing the flame without excessively decreasing total pressure [1]. When used as an integrated fuel injection/flameholding approach [2], cavity flameholders

have become even more attractive in supersonic combustors and received more and more attention.

Ben-Yakar et al. [3] used high-speed framing schlieren and OH-Planar Laser-Induced Fluorescence (PLIF) to investigate hydrogen transverse jet injected upstream of a cavity in air cross-flow simulating flight Mach 10 conditions, where auto-ignition was achieved and OH fluorescence appeared first in the recirculation upstream of the jet and extended along outer edge of the jet plume. O'Byrne et al [4] used OH-PLIF to investigate the supersonic combustion with horizontal injection from the aft wall of a cavity and found combustion occurred in the shear layer above the cavity rather than in the recirculating cavity flow.

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However, Jeong et al [5] found the cavity acted as a flameholder for the case of upstream injection. Micka et al [6–9] investigated the combustion characteristics of a dual-mode scramjet combustor with cavity flameholder, and found that the combustion was anchored at the cavity leading edge at low stagnation temperature and stabilized a short distance downstream of the fuel injection jet in the jet-wake at high stagnation temperature.

Gruber et al [10] studied the mixing and combustion in a supersonic flow using cavity flameholders. It was found that an imposed shock train had a significant impact on the mixing and chemical reaction processes that occurred in the cavity flameholder. This feature caused the cavity shear layer to separate, which effectively increased the volume of the cavity and the air entrainment. Rasmussen et al [11,12] investigated stability limits and flameholding mechanism of cavity-stabilized flames with direct cavity injection. When injected from the aft wall, the fuel came into immediate contact with hot combustion products from the reaction zone under the shear layer. Primary combustion occurred under the shear layer and in the aft region of the cavity volume. In contrast, when fuel was injected from the floor, a jet-driven recirculation zone of hot products near the upstream wall of the cavity served as a flameholder. The reaction then occurred on the underside of the shear layer. Sun et al [13,14] studied the combustion in a supersonic combustor with hydrogen injection upstream of cavity flameholders using OH-PLIF and hybrid Reynolds-Averaged Navier–Stokes (RANS)/Large Eddy Simulation (LES). It was shown that an approximately steady flame existed in the cavity shear layer and hot combustion products were transported into the injection jet by the vortex interaction of the jet-with-cavity shear layer, where the counter-rotating vortex induced by the jet and the cavity shear layer played an important role.

Although several important phenomena and characteristics of the cavity-organized supersonic combustion are realized, there are still many open questions regarding the physical mechanisms of ignition and flameholding under various injection conditions. The present work focuses on flameholding characteristics in a supersonic combustor with hydrogen injection upstream of a cavity flameholder.

2. Experimental and numerical descriptions

2.1. Experimental setup

The experiments are carried out at National University of Defense Technology in a recently developed direct-connected rig. The model scramjet combustor is installed behind the nozzle of the air heater, which heats the air by means of air/O₂/

alcohol combustion to simulate flight Mach six conditions, resulting in a Mach 2.52 and mass flow 1 kg/s stream in the combustor entrance. The run time is 5–6 s for the air heater and 0.8–1 s for the fuel injection, and the non-cooling supersonic combustor walls are directly exposed to the atmosphere. Detailed flow conditions at the nozzle exit and fuel jet exit are listed in Table 1, where the fuel is 99.5–99.8% pure H₂.

Schematic of the test section is shown in Fig. 1. The combustor has a constant width of 50 mm and height of 40 mm. A cavity with depth $D = 8$ mm, length-to-depth ratio $L/D = 7$ and aft angle of 45° is mounted on the bottom side, and an injector with orifice diameter 2 mm is fixed 10 mm upstream of the cavity leading edge. Quartz glass windows can be mounted on the top and side walls to allow optical access. OH-PLIF, flame luminosity and schlieren are introduced to characterize flow and combustion. The exposure time of PLIF is 50 ns. The exposure time and frame rate of flame luminosity and schlieren are 0.25 ms and 4000 frame/s, respectively. The PLIF system includes an Nd:YAG laser, a dye laser, a frequency doubler and an intensified charged-coupled device (ICCD) system. The output beam from Nd:YAG laser is at 532 nm. It pumps the dye laser to generate the laser beam at 567.106 nm. Then the output from the dye laser is transferred into the doubler, which transforms it into an Ultraviolet (UV) laser beam at 283.553 nm and 18 mJ/pulse. The UV beam is adjusted to a laser sheet by a group of lenses. The thickness of the plane beam is about 0.2 mm and the width is about 50 mm. The PLIF image is photographed by an ICCD camera. PLIF measurements on y – z planes are calibrated from the original images where the camera is arranged angled to the plane beam.

2.2. Numerical treatment

A hybrid RANS/LES method [15] blending the Spalart–Allmaras RANS model [16] (used for near-wall regions) and Yoshizawa sub-grid scale (SGS) model [17] (used for regions away from the wall) is used as turbulence model. An assumed sub-grid PDF (Probability Density Function)

Table 1
Experimental conditions.

Parameter	Air	Jet
T_0 , K	1486	300
P_0 , MPa	1.6	0.6/1.2/1.8
Ma	2.52	1.0
Y_{O_2} , %	23.38	0.0
Y_{H_2O} , %	6.22	0.0
Y_{CO_2} , %	10.16	0.0
Y_{N_2} , %	60.24	0.0
Y_{H_2} , %	0.0	100.0

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