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Ethylene flame-holding in double ramp flows

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ABSTRACT

In this work, ethylene flame-holding in supersonic flows was investigated using a shock tunnel. The experiments were conducted at flow stagnation temperatures ranging from 1270 to 1810 K. The two-dimensional test model consisted of a double-ramp inlet and a constant-area combustor with a recessed wall cavity. The two fuel injectors were located at the inlet and the other upstream of the cavity. Shadowgraph and flame chemiluminescence images were captured for optical visualization. The inlet injection images showed various flame-holding patterns. At 1270 K, the flame was not maintained. At 1540 K, the flame was maintained inside the cavity, and the condition provided continuous combustion during the steady flow. At 1810 K, strong flame signals were observed from the inlet to the cavity and downstream. At 1540 K, the inlet injection with a low fuel pressure showed a gradual flame quenching in the cavity during flow establishment. On the other hand, the same injection in the combustor showed flame-holding in the shear layer above the cavity. The results showed that the flame patterns are strongly influenced by the flow stagnation temperature and the location of fuel-injection.

1. Introduction

For the development of scramjet engines, an understanding of the fuel ignition and combustion processes in supersonic flow is important. Compared to hydrogen, hydrocarbons such as ethylene and methane have high volumetric energy density [1]. However, the hydrocarbons suffer from an ignition delay time [2] too long to be used as the fuel. Therefore, burning hydrocarbon fuels in the scramjet flowpath typically requires a flame-holding device to facilitate the ignition and combustion.

Comprehensive review works on flame-holding cavities [3,4] outline that a wall cavity installed in the combustor reduces the ignition delay time and creates a recirculation zone. As a result, the zone locally slows down the fuel–air mixture to subsonic speeds. Using this cavity flame-holder concept, the Air Force Research Laboratory (AFRL) [5–7] conducted an extensive investigation on hydrocarbon fuel combustion in supersonic flows. The AFRL used two-dimensional and axisymmetric model geometries with particular attention paid to the combustor. They found that the ethylene flame could be maintained over a wide range of equivalence ratios ($0.2 < \phi < 1.0$) by a recessed wall cavity. Researchers in the University of Michigan [8–14] conducted extensive studies on a dual-mode ramjet/scramjet combustor model. Observations indicated that, in scramjet mode operation, the flame was anchored at the cavity leading edge and stabilized at the cavity shear layer. Cai et al. [15,16] further tested a rearwall-expansion cavity configuration in a direct-connect combustor to compare the different ethylene fueling and ignition locations. By implementing the laser-induced plasma [17] system on the cavity floor, they also observed that the flame ignition process is closely related to the cavity fueling scheme and interactions with the flow-field.

In Australia, extensive experimental investigations on scramjet engines in high-enthalpy flows have been conducted using the University of Queensland's T4 shock tunnel [18]. Gardner et al. [19] first employed the fuel injection in the inlet to visualize the flow-field of a two-dimensional scramjet model. Despite the inlet injection, which created a fuel–air mixture upstream of the combustor, there was no sign of pre-ignition in the inlet. Applying the inlet injection to the three-dimensional inlet, Suraweera and Smart [20] found the engine started up to the equivalence ratio of 0.41 with the off-design flow condition. Turner and Smart [21] applied the inlet injection in their Mach 8 scramjet flowpath. Surface pressure distribution showed robust hydrogen combustion in the flowpath up to the global equivalence ratio (ϕ) of 0.92; although there was an increase in drag due to fuel injection, inlet fueling proved to have a potential of providing an extra fuel–air mixing length upstream of the combustion chamber. Continuing with a downscaled engine, the freejet testing of HIFiRE 7 scramjet by Chan et al. [22] successfully demonstrated the merit of inlet injection in sustaining the dual-mode combustion. Recently, Denman et al. [23,24] con-

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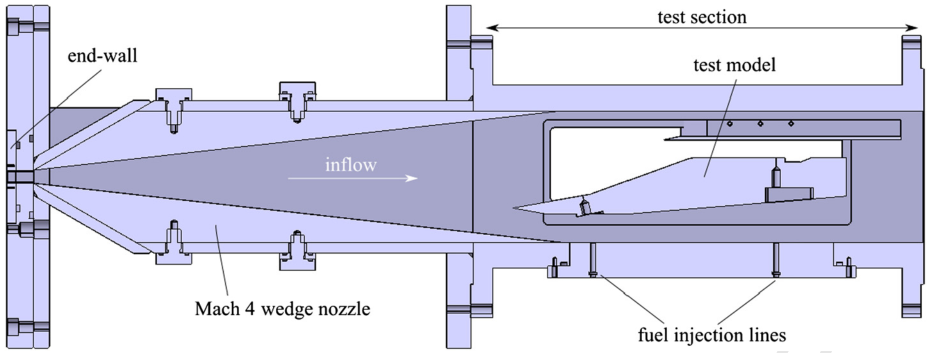

Fig. 1. Schematic of the nozzle and the test section with a side-mounted model.

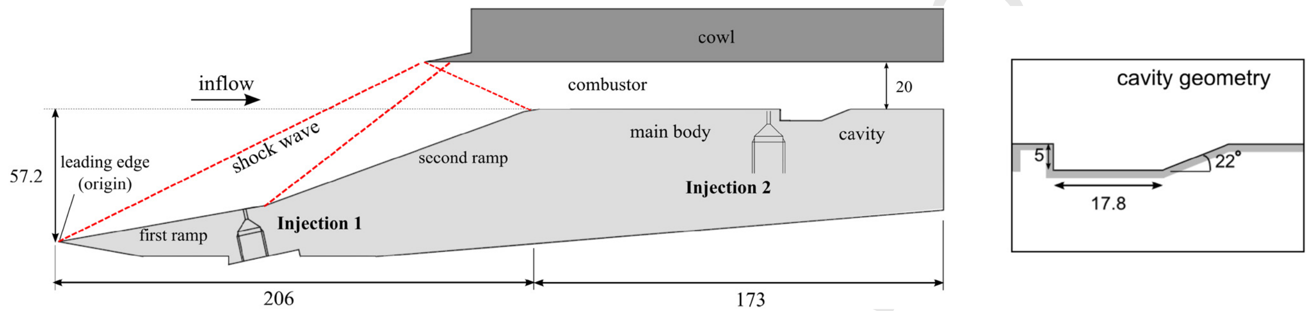

Fig. 2. Schematic of the test model. Dimensions are in millimeters unless otherwise specified.

ducted a series of hydrocarbon fuel injection in the same engine with an extra wall cavity and a spark ignition system. By measuring the internal pressures along the engine flowpath, they found that the cavity could successfully facilitate the ethylene combustion.

Inlet injection in scramjets enhances the mixing process by providing a longer mixing length and higher mixing efficiencies [25,26], thereby shortening the required combustor length. However, an excessive inlet injection incurring a significant entropy generation [27] will degrade the engine performance. In addition to the porthole injection, different inlet fueling mechanisms such as cantilevered ramp injectors [28,29] to suppress the premature ignition in shock-induced combustion ramjets and porous injectors [30] to further increase mixing and combustion efficiencies were developed. Nevertheless, there are only a few inlet-injection experimental data obtained from high-enthalpy flow conditions [19–24]. The existing data are usually confined to flow enthalpies that are suitable for high Mach number ($M_\infty > 7$) flows. To the authors' knowledge, there is yet no shock tunnel experiment that visualizes the coupling between flow-field and ethylene flame-holding characteristics of scramjet-like internal flows. In particular, an understanding of the flow-field characteristics from the inlet to the combustor and their coupling with the flame-holding process is limited.

Recently, the present authors have examined ethylene jet and flame interactions in the shock tunnel. Using a combustor model including a cavity and a cowl, Park et al. [31] determined that the flame can be maintained inside the cavity at a flow stagnation temperature of 2080 K. With different cowl shock positions at 1860 K, Chang et al. [32] categorized the flame patterns into three different types of interaction: flame quenching, flame-holding inside the cavity, and flame-holding at the cavity shear layer. The enhancement of fuel–air mixing and combustion was considered to be caused by the interaction of cowl shock impingement on the fuel jet and the use of the wall cavity. From the experience, a noteworthy conclusion can be drawn: shock impingement location and flame-holding are closely related.

In light of the recent investigations, the current work aims to extend the understanding of ethylene auto-ignition and flame holding using a scramjet-like model geometry. Compared to the model used in the previous work [31,32], the new model has a longer flowpath from the double-ramp inlet to the combustor. In the first part of this paper, we inspect the flame-holding characteristics in different flow stagnation temperatures, especially when the temperature is lower than the recent finding of 1860 K. Next, two different fuel injection locations are considered to inspect the flame and their coupling with the flow-field characteristics of double ramp flows.

2. Experimental details

2.1. Test facility

The experiments were conducted in a shock tunnel [32]. The test facility supplies a uniform test flow via a nominal Mach 4 nozzle. The facility consists of three main sections: a shock tube, a nozzle, and a test section. The shock tube consists of a 2.1-m driver tube, a 0.24-m transition tube, and a 10-m driven tube. The driver and the transition tubes were filled with helium. The driven tube was filled with the test gas, air. When the diaphragms, located at both ends of the transition tube, ruptured, a shock wave is formed. The wave travels through the driven tube; it nearly stagnates the test gas (dry air) by reflection at the end wall. Fig. 1 shows a schematic of the nozzle and the test section with a side-mounted model. The side walls of the nozzle, the test section, and the test model are direct-connected. The two-dimensional wedge nozzle is connected to the end-wall of the driven tube to expand the flow. The model is placed inside a rectangular cross-sectional test section.

2.2. Test model

Fig. 2 shows a schematic of the test model. The two-dimensional model consisted of a double ramp, a main body with a cavity,