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Experimental investigation on laser-induced plasma ignition of hydrocarbon fuel in scramjet engine at takeover flight conditions

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ABSTRACT

Laser-induced plasma ignition of an ethylene fuelled cavity is successfully conducted in a model scramjet engine combustor with dual cavities. The simulated flight condition corresponds to takeover flight Mach 4, with isolator entrance Mach number of 2.1, the total pressure of 0.65 MPa and stagnation temperature of 947 K. Ethylene is injected 35 mm upstream of cavity flameholder from four orifices with 2-mm-diameter. The 1064 nm laser beam, from a Q-switched Nd:YAG laser source running at 10 Hz and 940 mJ per pulse, is focused into cavity for ignition. High speed photography is used to capture the transient ignition process. The laser-induced gas breakdown, flame kernel generation and propagation are all recorded and ensuing stable supersonic combustion is established in cavity. The highly ionized plasma zone is almost round at starting, and then the surface of the flame kernel is wrinkled severely in 150 μs after the laser pulse due to the strong turbulence flow in cavity. The flame kernel is found rotating anti-clockwise and gradually moves upstream as the entrainment of circulation flow in cavity. The flame is stabilized at the corner of the cavity for about 200 μs, and then spreads from leading edge to trailing edge via the under part of shear layer to fully fill the entire cavity. The corner recirculation zone of cavity is of great importance for flame spreading. Eventually, a cavity shear-layer stabilized combustion is established in the supersonic flow roughly 2.9 ms after the laser pulse. Both the temporal evolution of normalized chemiluminescence intensity and normalized flame area show that the entire ignition process can be divided into four stages, which are referred as turbulent dissipation stage, combustion enhancement stage, reverting stage and combustion stabilization stage. The results show promising potentials of laser induced plasma for ignition in real scramjets.

1. Introduction

Reliable ignition in scramjet engines is a significant challenge because of the restrictive reactive environment, where fuel injections, mixing, ignition and flame propagations have to be completed within residence time of milliseconds [1]. Compared with hydrogen fuel, the comparatively longer ignition delay times of hydrocarbon fuels make this task more difficult. Especially at takeover flight speeds (Mach numbers ≈ 4), the low pressures and temperatures in the supersonic flow prohibit auto-ignition. Thus, external sources have to be provided for ignition.

In recent years, a cavity flame holder have been widely used to assist mixing as well as for flame holding as a result of a low-speed and high-temperature recirculation region established in the cavity, resulting in shorter ignition delay and longer residence time. A fraction of the fuel–air mixture entrained into the cavity recirculation region can be ignited and a local flame could be stabilized in the cavity. The heat release generated locally and the transportation of reactive species formed in the recirculation region can in turn be used to initiate, accelerate, and sustain chemical reactions in the core flow of the combustor. Typically, deflagration is the dominant mode of combustion in scramjet engines. However, Sun et al. [2] found that if a fuel/air premixed region from the injection to the cavity flameholder existed, the cavity pilot flame could reignite the fuel/air mixture, and the maximum absolute flame speed was higher than half of the CJ detonation speed, which suggested that the flame propagation was in a transition from deflagration to detonation (DDT). The theoretical and experimental investigations of DDT processes in detonation tubes with cavities were performed by Smirnov et al. [3–5]. It was proved that cavities in the ignition part of the tube can promote DDT and shorten the predetonation length. The importance of the flow inhomogeneity and contact surfaces resulting from shock wave interaction on the detonation initiation were emphasized. Cai et al. [6] numerically studied cavity-based detonation in supersonic hydrogen-

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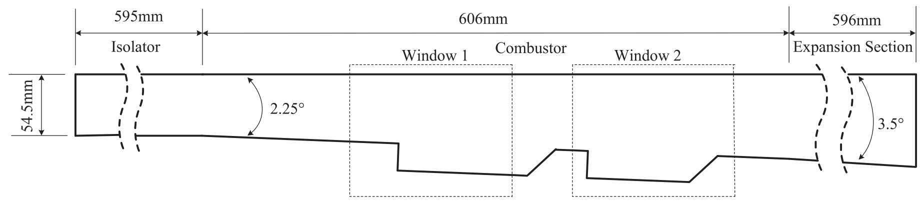

Fig. 1. Schematic of supersonic combustor and cavity installation.

oxygen mixture. Results showed that the cavity can help realize detonation initiation and promote detonation propagation in the supersonic combustible mixture.

Various ignition schemes based on cavity flameholder have been applied to achieve reliable ignition. Dual-cavity ignition scheme was employed by Li et al. [7] to enhance the ignition ability of a scramjet combustor fueled by kerosene. Bao et al. [8,9] applied spark discharge to ignite a kerosene fueled cavity at Mach 4 flight condition at 17 km. The ignition probabilities of the local ignition were analyzed based on the plentiful of experimental data. Cai et al. [10–12] investigated the ignition process in a model scramjet combustor with rearwall-expansion cavity fueled by ethylene using a traditional spark plug. Ombrello [13] compared two different energy deposition techniques: a spark discharge and pulse detonator. Spark discharge ignition was a more passive process, while pulse detonator ignition was extremely disruptive to the cavity flow dynamics. The nonequilibrium plasma produced by a nanosecond pulsed discharge has been shown to reduce the ignition delay times of both H_2-air mixture and ethylene-air mixture [14,15]. Other techniques such as plasma torches [16], pilot hydrogen [17] and mechanical throttle [18] were proved to have positive effect on ignition too.

In recent years, laser-induced plasma ignition (LIPI) is thought to be a promising ignition technique in practical application. Compared with traditional electrical discharge, laser-induced plasma has a few advantages. The rate and amount of energy deposition can be precisely controlled using laser ignition. Ignition timings can be controlled accurately due to faster time scales (~ns) than electric spark (~100 μs), allowing precise synchronization with advanced laser diagnostics instruments. This point is particularly fascinating as ignition in supersonic flow is a highly transient process. Additionally, a flexible selection of the ignition location can be achieved. The laser-induced breakdown can be placed at the point where the local equivalent ratio equals to 1 as a result of an inhomogeneous fuel distribution in the complicated supersonic flow consisting of shocks, shock wave/boundary layer interaction and cavity shear layer. Using laser to produce plasma for ignition, electrical-magneto interference can be avoided, improving the system safety of scramjet engines. With these advantages, many researchers have investigated laser-induced plasma ignition. A review of the physical process of laser-induced plasma ignition was provided by Phuoc [19]. Four mechanisms with laser ignition can be used to induce spark: thermal initiation, non-resonant breakdown, resonant breakdown, and photochemical ignition. Non-resonant breakdown is the most frequently adopted ignition mode to initiate combustion because it does not require a close wavelength match to photo-dissociate a particular target species. Also, non-resonant breakdown has the most similarities with traditional electrical discharge among the four ignition mechanisms. Gebel [20] investigated the transition from laser-induced breakdown plasma to a flame kernel in two-phase flows by optical emission spectroscopy. Recombination reactions to atoms and later to diatomic radicals were demonstrated inside the decaying spray breakdown plasma and the transition from a breakdown plasma to a flame kernel proceeded within few microseconds after the laser pulse. Beduneau [21] investigated the minimum energy necessary to ignite a laminar premixed methane air mixture experimentally. Effects of the flow velocity, equivalence ratio, and lens focal length on the minimum ignition energy (MIE) were analyzed. The MIE values were higher than those observed using spark plugs. However, these differences tended to disappear at the lean and rich fuel limits. Similar conclusions were also reached by McNeill [22]. The higher energy cost of laser spark formation (both breakdown and heating) and absence of supplemental heating of the kernel after the shock wave were two major reasons for a higher MIE. Mulla [23] investigated the early stages of flame-kernel development in laser-induced spark ignited mixtures of various gas compositions under different flow regimes. All the stages of kernel development from the elongated kernel to the toroidal formations and the subsequent appearance of a front-lobe were visualized through OH-PLIF images. Cardin [24] obtained a clear turbulent ignition transition on the MIE as a function of the rms velocity (u') and reconfirmed two modes of ignition. A characteristic chemical time (τ_{CB}) was defined as the start of the chain-branching reactions. Physically, this chemical time corresponded to the time when the initial chemical reactions of the ignition process released enough heat to compensate for heat losses and to enable a self-sustained reaction in successful ignition. When the smallest time scales of the turbulence were larger than the τ_{CB} values, the hot kernel/turbulence interaction occurred after the initiation of the chemical reactions. Hence, the MIE was similar to that under laminar conditions. When the smallest time scales of the turbulence were smaller than the τ_{CB} values, turbulence may have affected and interacted with the hot kernel before the initiation of chain-branching reactions occurred. Larger amounts of deposited energy were therefore required to compensate for this turbulent dissipation and to attain a self-sustained flame. However, applications of LIPI in scramjet engines are rather limited. Brieschenk [25,26] demonstrated that LIPI can be used to promote the formation of hydroxyl in a hypersonic flow for the first time. However, the combustion in the hypersonic flow was not stabilized due to absence of flameholder. Two different ignition strategies were introduced, which were referred as fuel-jet LIP ignition and shear-layer LIP ignition. When Ar was used as a plasma buffer gas, the ignition effectiveness greatly increased. The study identified the importance of duration time of plasma on ignition. Yang [27] and Li [28] performed LIPI in a model scramjet combustor with cavity flameholder successfully. The simulated flight conditions were Ma 5.5 at 23 km altitude. Successful ignition and sustained combustion of gaseous ethylene and liquid kerosene were obtained. However, at the takeover flight conditions (Ma ≈ 4), where the total temperature and pressure of the supersonic flow are much lower, the feasibility of LIPI in scramjet combustors still remains to be examined.

In the present study, cavity ignition of gaseous ethylene in a scramjet combustor using LIPI is investigated. The simulated flight condition is Ma 4 at 15 km, and the isolator entrance has a Mach number of 2.1, a total pressure of 0.65 MPa and a stagnation temperature of 947 K. Successful ignition and sustainable combustion are achieved. High speed photography is used to record the growth of flame kernel generated by LIPI and local flame spreading process until the cavity-stabilized combustion is established in the supersonic flow. The laser induced plasma ignition process in supersonic flow is analyzed in detail.

2. Experimental installation

A direct-connect test facility was used for the experiments. The facility was composed of an air heater, a supersonic nozzle and a scramjet model combustor. The air heater burned pure alcohol and oxygen