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Laser-induced plasma ignition studies in a model scramjet engine

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ABSTRACT

An experimental investigation of the behavior of laser-induced plasma (LIP) ignition for scramjet inlet injection is presented. The presented results demonstrate for the first time, that LIP can be used to promote the formation of hydroxyl in a hypersonic flow. The temporal evolution of the LIP-ignited region is monitored using the planar laser-induced fluorescence technique on the hydroxyl radical. This study is the first laser spark study in a hypersonic flow, shown to generate combustion products where they would not otherwise occur.

1. Introduction

Providing ignition in supersonic flows using traditional flame holders relies on the principle of establishing stable, subsonic combustion zones that ignite the adjacent supersonic stream. Introducing injector struts or bluff bodies into the supersonic combustor flow for flame holding results in high entropy increases and can cause the engine to unstart [1]. Wall cavity flame holders minimize the introduced entropy rise but may only provide ignition above the cavity, rather than anchoring the flame at the cavity [2]. For this reason, cavity type flame holders work efficiently at sonic and supersonic speeds [3,4], but are less effective at hypersonic speeds.

This study examines the applicability of providing ignition in a hypersonic flow using laser-induced plasma (LIP). In terms of electromagnetic bandwidth, excitation using lasers presents the possibility of a more controlled method of energy deposition than thermal excitation using discharge-based methods. LIP ignition has been demonstrated successfully in controlled, laboratory environments using relatively high gas pressures and well mixed, low-speed flows [5,6]. This study aims to answer the question of whether or not a non-resonant LIP can provide ignition in a hypersonic, turbulent non-premixed flow with conditions comparable to those experienced by a scramjet-powered vehicle. Potential difficulties are:

- Spark ignition in turbulent flows has a stochastic nature and the probability of establishing a flame depends on the local strain rate [7]. The strain rates that are present in the interaction region between a sonic jet and a hypersonic crossflow are high and can exceed flame extinction strain rates.
- The fuel and air streams in a scramjet engine operating a high Mach number are poorly mixed, and engine efficiency is typically determined by the quality of fuel–air mixing. The residence time for atmospheric air ingested into a scramjet inlet and exiting from the engine nozzle is of the order of one millisecond and the injected fuel must mix with the air stream within tens of microseconds [8].
- The flow in a scramjet-powered engine is of low density and high velocity. The gas density at an altitude of 30 km is roughly 1/70 the density at sea level, while the pressure is roughly 1/90 of the atmospheric pressure at sea level. The laser-absorption threshold is a function of gas pressure implying potential difficulties in applying LIP ignition at low pressures. Ignition delay and reaction times scale with gas pressure and the ignition delay time for a stoichiometric hydrogen-air mixture at a pressure of 1/90 atm and a temperature of 1500 K, which is twice the autoignition temperature at that pressure [9,10], is of the order of 1 ms [11]. This translates into an ignition delay length of the order of 2 m for a flow speed of 2000 m/s. This example calculation clearly demonstrates the great difficulties that exist for LIP ignition to be effective in such high-speed flows.

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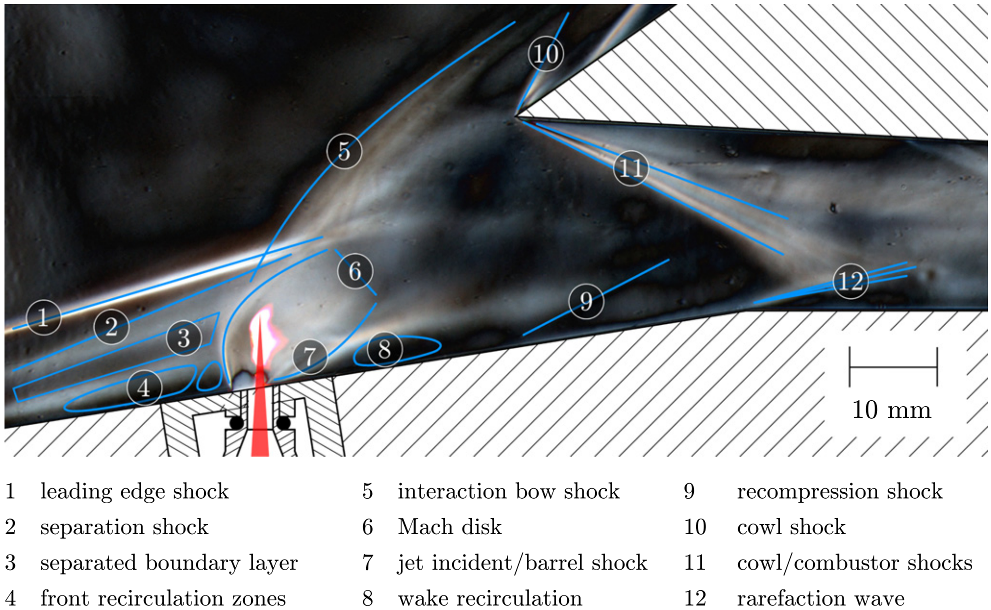

Fig. 1. Schlieren image of flowfield on the compression ramp; flow features at their approximate locations are superimposed as a line drawing.

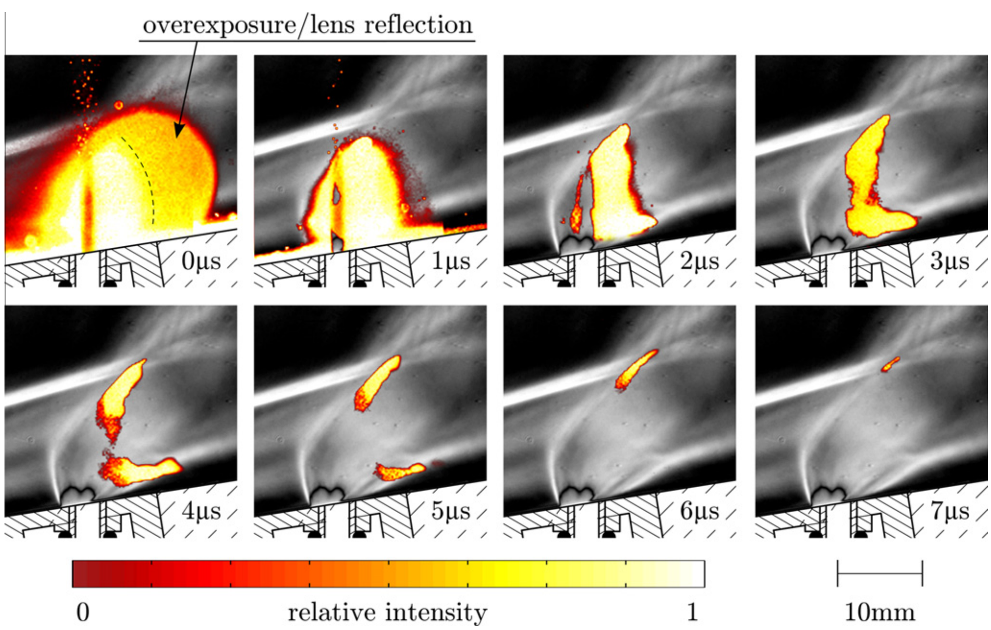

Fig. 2. Luminosity in the shear-layer LIP ignition experiment.

There are currently no experimental data available in the literature regarding the effect of laser energy deposition on ignition and combustion in a hypersonic, turbulent non-premixed flow. Laser ignition has the potential to fill a gap in the methods of igniting a hypersonic flow that other methods cannot adequately address. This warrants a fundamental study to investigate whether or not a LIP can generate combustion radicals in a hypersonic flow where autoignition does not occur.

2. Experimental arrangement, results and discussion

The LIP ignition experiments presented in this paper were conducted in the T-ADFA free piston shock tunnel using a flow condition with a total specific enthalpy of 2.7 MJ/kg and a freestream velocity of 2075 m/s. The scramjet model features a rectangular duct with a 9° compression ramp, followed by a constant-area combustor. Hydrogen is injected through four 2-mm-diameter holes located on the compression ramp of the model, which are distributed across the compression ramp, 120 mm downstream of the leading edge. The LIP is formed in the shear layers 1.7 mm downstream of the injectors. The laser accesses the flow through a 3-mm-diameter open port located mid-way between the two inner injector holes. The LIP is formed by a Q-switched ruby laser, focussed using a 100-mm-focal-length lens. Pulse energies of 750 mJ are used in this experiment. A significant portion of the laser energy is transmitted through the focal region, and is unable to contribute in the plasma formation process. A series of experiments in a gas cell have shown that 54% of the laser energy is absorbed by the LIP in the scramjet experiment The flowfield on the compression ramp is depicted in Fig. 1.

The underexpanded hydrogen fuel jet expands into the crossflow forming a barrel shock (7) which separates the upstream