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Experimental research of air-throttling ignition for a scramjet at *Ma* 6.5

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KEYWORDS

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Abstract An experimental investigation on ignition characteristics with air-throttling in an ethylene-fueled scramjet under flight *Ma* 6.5 conditions was conducted. The dynamic process of air-throttling ignition was explored systematically. The influences of throttling parameters, i.e., throttling mass rate and duration, were investigated. When the throttling mass rate was 45% of the inflow mass rate, ambient ethylene could be ignited reliably. The delay time from ignition to throttling was about 45–55 ms. There was a threshold of throttling duration under a certain throttling mass rate. It was shorter than 100 ms when the throttling mass rate was 45%. While a 45% throttling mass rate would make the shock train propagate upstream to the isolator entry in about 10–15 ms, four lower throttling mass rates were tested, including 30%, 25%, 20%, and 10%. All of these throttling mass rates could ignite ethylene. However, combustion performances varied with them. A higher throttling mass rate made more ethylene combust and produced higher wall pressure. Through these experiments, some aspects of the relationships between ignition, flame stabilization, combustion efficiency, and air-throttling parameters were brought to light. These results could also be a benchmark for CFD validation.

1. Introduction

The resident time of fuel in a scramjet combustor decreases remarkably under a flight *Ma* 6.5 condition than that of a *Ma* 4.5 condition.[1] Although hydrocarbon fuels have greater fuel densities and endothermic cooling capabilities than hydrogen,[2] it is more difficult for hydrocarbon fuels to mix sufficiently and combust with inflow air because of their long ignition delay time.[3] Therefore, some aided ignition techniques must be employed to increase resident time and facilitate local mixing.[4,5] Air-throttling is a widely used ignition method, which injects high-pressure air into a scramjet combustor to produce a throttling effect.[6] Throttling can slow down the flow speed of inflow air and increase the mixing time for the fuel. A pre-combustion shock train can be formed and a local environment with a high temperature and a low flow speed can be

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established. Furthermore, shock/boundary interaction could produce flow separation near the wall and distortion of the main flow, which would ease the difficulty of ignition.[7–10]

Previous investigations on ignition and combustion in scramjets with air-throttling are briefly summarized in Table 1. T_0 is total temperature of inflow, p_0 is total pressure of inflow, Ma_i is Mach number at isolator entry. Mathur et al. conducted an experiment to research air-throttling aided combustion.[11] It was shown that if the heat release from combustion was strong enough to maintain a pre-combustion shock train, combustion could be stabilized; otherwise, combustion couldn't persist. Donbar et al. studied the influence of throttling timing.[12] Viacheslav et al. ignited preheated methane with air-throttling and a methane/air torch. Flame-out happened after throttling off if the heat release was not enough to stabilize combustion.[13] Li et al. investigated the transient dynamics of air-throttling ignition. The dynamic optimization of air-throttling was achieved by implementing a genetic algorithm in the quasi-one dimensional code.[14,15] Noh et al. studied the ignition process of ethylene with air-throttling numerically under a Ma 3 condition.[16] Li et al. used the computational fluid dynamics (CFD) method to study the cold and reacting flow field in a combustor with/without air-throttling.[17,18] Bao et al. ignited liquid kerosene with air-throttling and a kerosene/oxygen torch.[19] Tian et al. studied the flow-field of a scramjet and flame stabilization with air-throttling using the CFD method.[20]

Although a series of excellent results has been gotten, most of them were accomplished by CFD. The other experimental results were mainly conducted under flight Ma 5 or less conditions. So far there is almost no experimental investigation on ignition characteristics under flight Ma 6.5 conditions, when air-throttling is the unique aided ignition technique. However, the re-ignition ability offered by air-throttling is important for a scramjet cruising at a high Mach number. A higher flow speed increases the difficult of ignition and makes the ignition process different from that under a lower speed. Meanwhile, the throttling mass rate and duration must be precisely controlled and optimized. An excess throttling mass rate or a too long throttling duration would result in the shock train propagating upstream to the isolator entry and make the inlet un-start. However, insufficient throttling could not produce a low-speed region with a high local pressure and temperature to facilitate ignition.

In this study, the dynamic process of air-throttling ignition in an ethylene fueled scramjet is explored systematically. The influences of throttling parameters, i.e., throttling mass rate and duration, are investigated. The inflow conditions simulate those of flight Ma 6.5. The development of flame with air-throttling is exposed by wall pressure measurements and high-speed photographs. Through these experiments, some aspects of the relationships between ignition, flame stabilization, combustion efficiency, and air-throttling parameters are brought to light.

2. Experimental setup

2.1. Pulse combustion wind tunnel

The pulse combustion wind tunnel is a directly-connected experiment facility. It consists of several subsystems, including an oxygen-rich-air supply system, a hydrogen supply system, a combustion heater, a facility nozzle, and a vacuum tank. The wind tunnel uses hydrogen as fuel combusting with oxygen-rich-air to produce experiment inflow. Meanwhile, the mole fraction of oxygen after combustion remains 21% just as the same as that in atmosphere.[21–23]

Once stable combustion is established in the combustion heater, the high-temperature gas would be accelerated by the two-dimensional facility nozzle to achieve a needed Mach number. Combined with the currently available Ma 2, 2.6, and 3 facility nozzles, the combustion heater is fine-tuned to simulate flight conditions from Ma 4 to 6.5. For the presented study, the experiment inflow conditions simulate those of fight Ma 6.5. The gas parameters at the scramjet isolator entry are listed in Table 2. The total temperature is measured by a platinum-rhodium Type-B thermocouple. The total pressure is calculated by the wall static pressure and the Mach number with the Rayleigh Pitot tube formula. The ratios of specific heat and combustion efficiency of the heater are supposed to be 1.36 and 0.85, respectively. The mass flows of hydrogen and oxygen-rich-air are computed by their supply pressures and the area of the sonic throat.

Table 1 Survey of investigations of ignition and combustion in scramjets using air-throttling.

Reference	Fuel	Condition	Injector	Flame holder	Igniter	Research method	Year
Mathur et al.[11]	Ethylene	$Ma_\infty = 4$–5	Flush-wall orifice	Cavity	Spark plugs/plasma torch	Experiment	2000
Donbar et al.[12]	Ethylene	$Ma_\infty = 4$–5	Flush-wall orifice	Cavity	Spark plugs	Experiment	2001
Viacheslav et al.[13]	Methane	$Ma_i = 2.0$ $p_0 = 0.7$ MPa $T_0 = 910$ K	Transverse orifice	Pylon	CH_4/air torch	Experiment	2003
Li et al.[14,15]	Ethylene	$Ma_\infty = 3.5$–5	Transverse orifice	Cavity		Experiment and CFD	2006
Noh et al.[16]	Ethylene	$Ma_\infty = 5$	Transverse orifice	Cavity		CFD	2010
Li et al.[17,18]	Ethylene	$Ma_\infty = 5$	Transverse orifice	Cavity	Spark plugs	CFD	2014
Bao et al.[19]	Kerosene	$Ma_i = 3$	Struts		Kerosene/oxygen torch	Experiment	2012
Tian et al.[20]	Ethylene	$Ma_\infty = 2$	Flush-wall orifice	Cavity	Pilot hydrogen	CFD	2015

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