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Experimental investigation on gliding arc discharge plasma ignition and flame stabilization in scramjet combustor

Rong Feng [a], Jun Li [a,*], Yun Wu [a], Jiajian Zhu [b], Xiliang Song [b], Xipeng Li [b]

[a] Science and Technology on Plasma Dynamics Laboratory, Air Force Engineering University, Xi'an 710038, China
[b] Science and Technology on Scramjet Laboratory, National University of Defence Technology, Hunan 410073, China

ARTICLE INFO

Article history:
Received 7 May 2018
Received in revised form 13 May 2018
Accepted 21 May 2018
Available online xxxx

Keywords:
Gliding arc
Supersonic flow
Lean ignition limit
Ignition process
Flame stabilization

ABSTRACT

Ignition and flame stability in supersonic flow have always been the key problems of research in scramjet. In addition, ignition is difficult and the cavity flameholder is susceptible to support the flame stability under extreme conditions such as low equivalent ratio. In recent years, gliding arc plasma is recognized to expand ignition and extinction limit with lower energy consumption in the field of plasma assisted ignition due to its heating and chemical effects. In this paper, a gliding arc igniter has been designed and compared with the traditional spark plug in order to quantify the ignition ability. The igniter has the same size with the spark plug, using low-power AC gliding arc to carry out ethylene ignition test in Ma = 2.52 Ma supersonic flow. The average power of gliding arc discharge is 1199 W. A high-speed camera and CH* chemiluminescence were used to make combustion diagnosis. Founded in the same discharge period, the lean ignition limit of the gliding arc is lower than the ignition limit of the spark. The average expansion of ethylene ignition limit is 17%. The ignition process is that gliding arc continues to generate the initial flame kernels during the discharge period, but it is extinguished continuously due to the strong convection. Until generating an initial flame kernel which can successfully propagate the flame. The ignition process can be divided into four stages. It continues to generate new flame kernels in flame propagation process. Gliding arc reignites the fuel and generates the new flame kernels after forming a stable flame, appearing intermittent ignition in the cavity. The high equivalent ratio can make ignition delay time shorter, generating initial flame kernels more frequently. The heating effect of the gliding arc and reignition character make the thermal product and ethylene occur intermittent combustion more often in the cavity, increasing the area of the combustion reaction. Gliding arc plasma can achieve combustion enhancement during the flame stabilization process. The shear layer of flame thickness increased by the average of 2 mm on S-B-1 and G-B-1 conditions. Compared with the traditional spark ignition, gliding arc broaden the lean blow-off limit in different stages may be the significant reason for broadening lean ignition limit. It concludes that gliding arc makes the flame's ignition limit closer to the flame's blow-off limit.

1. Introduction

Plasma assisted ignition in scramjet engines gets more attention in recent years [1–3]. The ignition in scramjet engines is difficult because the restrictive environment evaporation process and slow chemical kinetic reactions make the ignition delay time exceed the residence time of the fuel-air mixture in supersonic flow [4]. In addition, the cavity flameholder is susceptible to support the flame stability under extreme conditions such as low equivalent ratio. Thus, plasma assisted ignition is a significant technology to improve the ignition performance in scramjet engines, due to the strong influence on the ignition process [5–7].

Various plasma assists ignition applications have been developed: Leonov et al. [8,9] examined ignition and flameholding effects of the Quasi-DC discharge in a supersonic combustion chamber. A flame extinction is observed when the discharge is turned off. S.P. Kuo et al. [10] developed a versatile plasma torch for being an ignition aid within a supersonic-combustor. They found that the arc discharge have remarkable increased size with microwave. O. Macheret et al. [11,12] found that multi-spot and repetitively pulsed plasma ignition scheme could reduce the power budget by several orders of magnitude. S. Brieschenk et al. [13] investigate the behavior of laser-induced plasma (LIP) ignition for scramjet in-

* Corresponding author.
E-mail address: kltbwhy@126.com (J. Li).

https://doi.org/10.1016/j.ast.2018.05.036
1270-9638/

Please cite this article in press as: R. Feng et al., Experimental investigation on gliding arc discharge plasma ignition and flame stabilization in scramjet combustor, Aerosp. Sci. Technol. (2018), https://doi.org/10.1016/j.ast.2018.05.036

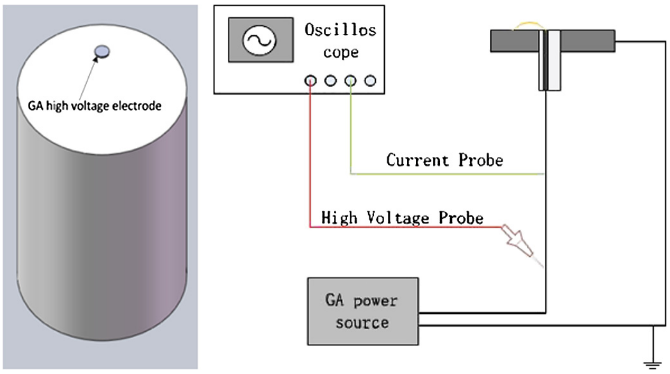

Fig. 1. Gliding arc plasma igniter and discharge system.

let injection, LIP can be used to promote the formation of hydroxyl in a hypersonic flow.

Gliding arc discharge is a significantly non-equilibrium plasma in previous work [14,15]. The gliding arc technology provides high-power non-equilibrium plasmas. Many reactive products, such as N_2, O_2, NO and OH, are generated in air plasmas by gliding arc discharges [16,17]. This technology is low-cost and treats a large number of chemical species which is good for ignition.

A great number of researchers have been focused on this area. The Gliding arc discharge applications were described in Fridman's studies [18,19]. To understand the basic mechanism of the plasma-flame interaction, Timothy Ombrello et al. [20] studied the effect of gliding arc discharge on the combustion enhancement of methane-air diffusion flames. It was shown that with gliding arc discharge of the airstream, up to 220% increase in the extinction strain rate. Jiajian Zhu et al. [21] investigated effects of the air flow rates the dynamics, ground-state OH distributions and spectral characterization of UV emission. The result showed that the intensity of ground-state OH distribution varied significantly with air flow rates. Gliding arc applied in NO_x reduction, hydrocarbon reduction has also been extensively conducted [22,23].

The research on ignition and flame stabilization of gliding arc discharge is absent, and the application of the AC gliding arc in the scramjet has not been founded in the present work. Due to the short residence time of the fuel-air mixture in scramjet engine, the research on plasma use in supersonic flow always needs high-power plasma source, which means huge power and volume weight [24,25]. The supersonic combustion generally uses the cavity-assisted stabilization [26]. Due to the low flow velocity in the cavity, it is a good choice to furnish the igniter [27]. In the previous studies on the gliding arc plasma, the evaluation of the gliding arc ignition capability is also few. In this paper, the low-power gliding arc ignition and flame stabilization have been studied. In order to quantify the ignition ability of gliding arc, the ignition capacity of the spark plug is compared to obtain the two kinds of lean ignition limits.

2. Experimental setup

2.1. Gliding arc plasma igniter and discharge system

Gliding arc plasma igniter comprises a nickel-copper alloy electrode and the ceramic insulator. The nickel-copper alloy electrode is the high voltage electrode, and the iron wall on the bottom of the cavity is the cathode, gliding arc is broken into the gap between nickel-copper alloy electrode and iron wall. As shown in Fig. 1, an electrode with a diameter of 1 mm are arranged in the semiconductor. The gap width between the electrode and the edge of ceramic is 3 mm. Gliding arc continued to slip on the iron wall with the flow. The discharge system is also presented in Fig. 1. A gliding arc power supply, with average power 2000 W and the maximum peak voltage of 20 kV is adopted. In order to quantify the average power, a high-voltage probe (P6015A) and a current probe (TCP0030A) were employed to measure the voltage and current signals, respectively, and they were recorded by a time-resolved oscilloscope (Tektronix DPO4104) when conducting the ethylene ignition experiment.

Table 1
Experimental inflow conditions.

Parameters	Air
T_0 (K)	1600
P_0 (MPa)	1.65
Ma	2.52
MO_2 (%)	21.6
MH_2O (%)	9.2
MCO_2 (%)	6.5
MN_2 (%)	62.7

2.2. Direct-connected test facility

The experiments were conducted in the NUDT direct-connected test facility. The nominal inflow conditions of the model scramjet combustor are listed in Table 1 [28]. The parameter error of the experimental system is controlled within 5%.

2.3. Scramjet combustor configuration

The cavity flame-holder is mounted on the bottom wall with an expansion angle of 3.1° and the igniter was located in the middle of the cavity bottom wall. The cavity in the combustor is a typical single-side expansion cavity. As shown in Fig. 2, the depth D, length L, width W and aft ramp angle A of the cavity is 16 mm, 80 mm, 50 mm and 45° respectively. Two fuel injection schemes were studied: an injection 50 mm upstream the cavity and an injection 170 mm upstream the cavity. Cases were labeled as Case A and Case B. All injectors were set vertical to the combustor inflow direction. The position of the pressure measurement hole is also marked in Fig. 2, where the positions 1–2 is located at the front of the cavity block and the positions 13–16 is located at the behind of the cavity.

The ignition timing is as follows. As shown in Fig. 3, the power source open after opening ethylene injection 50 ms, making the ethylene is fully mixed with the mainstream air. Two types of power supply continue to open 300 ms, turning off the power supply 250 ms then close the ethylene injection. This means that the criterion for success is whether the ignition is successful within 300 ms of discharge.

2.4. Flow visualization measurements

Two quartz windows were installed on side walls which the length and the width are 148 mm and 90 mm respectively, as shown in Fig. 4. A high-speed camera (FASTCAM SA-X2) was utilized to visualize the ignition and flame propagation processes ignited by gliding arc discharge and spark plug which was placed on the side of the experimental system. The frame rate of SA-X2 was set at 40,000 frames per second (fps) with a resolution of 1024 pixels by 280 pixels and an exposure time of 25 μs. A combination of a high-speed camera (FASTCAM SA3) equipped with a f/1.4 Nikon zoom lens and a bandpass filter (centered at 430 nm, with a 10 nm FWHM) were used to record CH* chemiluminescence for the stable flame which was placed on another side of the experimental system. The imaging of SX3 was performed at a shutter speed of 10,000 fps with a resolution of 512 pixels by 272 pixels and an exposure time of 100 μs.

Please cite this article in press as: R. Feng et al., Experimental investigation on gliding arc discharge plasma ignition and flame stabilization in scramjet combustor, Aerosp. Sci. Technol. (2018), https://doi.org/10.1016/j.ast.2018.05.036