Experimental Investigation on The Ignition limits of Plasma-assisted Ignition in Propane-Air Mixture

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Abstract: Recently, the Plasma-assisted Ignition has been explored for applications on varies of engines. The plasma ignition has been shown the special advantages in shorting the ignition delay time, improving the reliability, reducing the NOx emissions. plasma ignition technology can be widely applied to the power and energy field such as internal-combustion engine, turbo engine, turbofan engine, scramjet, near space engine and pulse detonation engine. This paper designs a plasma jet ignition experiments system, the plasma jet ignition of argon-discharge arc was investigated. Plasma jet ignition uses the characteristics of high temperature (as high as 5000K) to ignite flammable mixture. Through the plasma jet ignition experiments, we investigated the ignition limits of plasma jet ignition and spark ignition in propane-air mixture. The results show that the plasma jet ignition could extend the ignition limits of propane-air mixture obviously. The ignition limits extends with increasing air flow rates. The average ignition limits of spark ignition and plasma jet ignition are 2.34 and 2.57. The average ignition limits of propane-air mixture extends by 9.8%. The plasma jet ignition limits extends with increasing arc current, and the degree of extending plasma jet ignition limits increases with increasing air flow rates. The average ignition limits of 5.7A and 20.3A are 2.57 and 2.79. The average ignition limits of propane-air mixture extends by 8.5%. The plasma jet ignition limits extends with increasing argon flow rates. The average ignition limits of 200L/h and 250L/h are 2.79 and 3.08. The average ignition limits of propane-air mixture extends by 10.4%.

Keywords: plasma-assisted ignition, spark ignition, lean limits, rich limits, excess coefficient

1. Introduction

In recent decades, particular interests in applications of non-equilibrium plasma to the problem of plasma-assisted ignition and combustion have been observed [1-8]. Drastic change of flying speed and attitude, breathing exhaust gas from other aircrafts make the combustion chamber operating conditions worse and pose great threat to the safe operation of aero-engine. Controlling the processes of ignition and combustion in aircraft jet engines is crucial for their performances over a wide range of operation parameters including altitude, flight speed, and thrust. Reduction of ignition delay time, prevention of flame blowing-off, improvement of flame stability, the reliability of high-altitude reignition and extension of fuel flammability limits are the key technical problems in the enhanced combustion field of aero-engine.

The most common approaches [1-4] to ignite combustible mixtures are: (i) heated surfaces or filaments, (ii) pilot flames, (iii) spark discharges and plasma torches, and (iv) laser ignition. All these approaches are all based on purely thermal ignition mechanism, and initiation of the chemical reactions by rapidly raising the gas temperature is limited in a small volume. The ignition occurs only in a small volume which may result in an incomplete combustion due to the slow flame propagation speed compared with the flow speed. The research in Ref. [5, 6] shows that raising the gas temperature in a small volume can: (i) produce active radicals and trigger high activation energy chemical reactions, (ii) accelerate the rates of exothermic reactions. In this case, the ignition criterion can be obtained. Heat spreads to the surrounding cold flow though conduction and convection, and gradually causes combustion of the whole field.

Plasma jet ignition uses the characteristics of high temperature (as high as 5000K) to ignite flammable mixture. With big ignition energy and strong penetrating ability, it can greatly increase the starting reliability of aero-engine under extream conditions and improve the working reliability, combustion stability and performance of aero-engine combustion chamber under bad working conditions such as high altitude, high speed, high maneuverability[7-10]. F.Wang et al [11-14] developed a plasma igniter and applied it to the pulse detonation engine to reduce the ignition delay time and DDT (deflagration to detonation transition) time. The experimental results show that the ignition delay time is reduced by 5% and DDT time is also reduced remarkably. I. Matveev and S. Matveeva [15-16] carried out the plasma ignition experiment at 12 km altitude, which shows that plasma ignition has good reliability at high altitude. Therefore, plasma ignition technology can be widely applied to the aviation aerospace field such as turbo engine, turbofan engine, scramjet, near space engine and pulse detonation engine.

In this paper, the plasma jet ignition of argon-discharge arc was investigated experimentally. The ignition limits of both the plasma jet ignition and spark ignition are acquired. The influence of arc currents and argon flow rates of plasma igniter to ignition limits are also investigated. The results can get an intuitive understanding of plasma ignition.

2. Experiment setup

2.1 Experiment devices and diagnostic equipments

The plasma jet ignition experiment system is shown in Fig. 1 and illustrated in Fig.2. It is mainly composed of a combustion experimental section, a plasma igniter, a spectrometer, a high-speed CCD camera, temperature/pressure sensors, a gas analyzer, data acquisition system, etc. The combustion experimental section is 80×80×320 mm in six and propane-air mixture is supplied by a pipeline. Air is supplied by a single screw air-compressor (flow rates 42.8 m^3/min, pressure 0~8 atm). Air and fuel flow rates are measured by DYNZ cone flow meter and controlled by 3810 L electrical valves. The plasma torch intensity is controlled by the plasma jet ignition power voltage and current. Pressure sensor, temperature sensor and gas analyzer are used to acquire real-time data of pressure, temperature and gas components.

In order to make the fuel and air mix sufficiently and keep the flow field in the experimental section uniform, a honeycomb rectifying section is fixed in front of the combustion experimental section. The combustion experimental section mainly includes the observation window, plasma igniter, flame holder, pressure/temperature sensors and gas analyzer (see Fig.2). The exhausted gases from experiment section is discharged through the exhaust pipe, and controlled by electrical valve which can control the flow rates and pressure in the combustion experimental section. In order to satisfy the heat-resistant requirements of air release valve, a water-cooling section is designed specially in front of the air release valve.

Fig.1. Plasma jet ignition experiment system

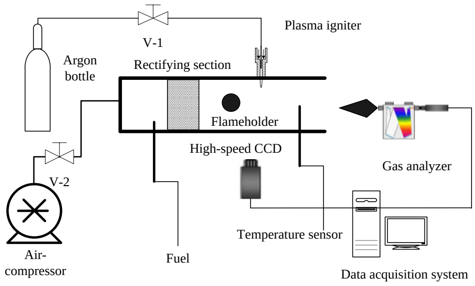

Fig.2. Schematic illustration of the experiment system

2.2 Plasma igniter and the ignition power

DC arc plasma igniter adopts high frequency and high voltage (3 kV, 1 kHz) to generate arc. The DC power keeps voltage at 24 V to maintain arc. The cathode and anode of plasma igniter are made of 75% W-Cu alloy, which can resist high temperature, corrosion, and has good conductivity. Exterior surface of the plasma igniter is coated with 3 mm thick insulated Bakelite, while the interior is filled with alumina ceramic to realize insulation and resist high temperature. The distance between cathode and anode is 2 mm. The working gas is argon which is supplied by argon bottle (flow rates 0-400 L/h, pressure 0-10 atm).

Since argon is an inert gas that can protect the electrodes so as to alleviate maximally problems such electrode ablation, discharge instability and short electrode life, etc. The plasma igniter in discharge state is shown in Fig.3. An obvious arc is generated at the exit of the igniter. The arc is about 30 mm long.

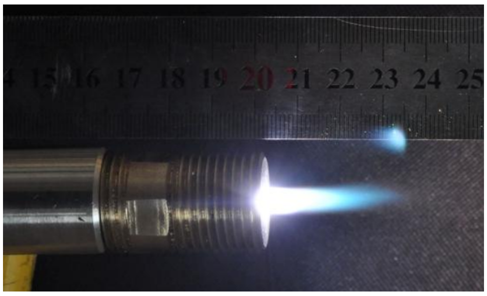

Fig.3. Plasma igniter

The picture of stable combustion was recorded by Canon camera (Fig.4). Because the temperature of plasma jet ignition is very high and the outlet jet is bright, a filter was used to weaken the light intensity to view the plasma jet process clearly.

Fig.4. Stable combustion of plasma jet ignition in the combustion chamber

3 Ignition limits of propane-air mixture in the combustion chamber

3.1 Ignition limits of plasma jet ignition and spark ignition

At argon flow rates 200L/h, arc current 5.7A, air flow rates 0~100m^3/h, when we applied plasma jet ignition and spark ignition in the combustion chamber, the rich limits and lean limits of propane-air mixture changes with increasing air flow rates (Fig.5).

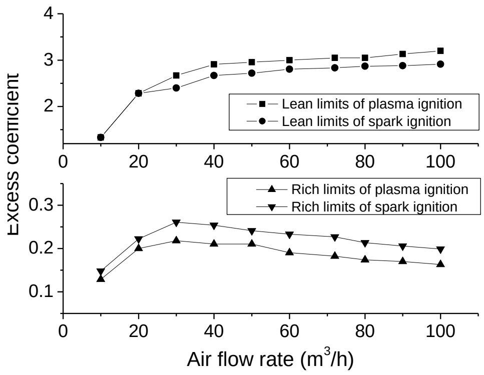

Fig.5. The ignition limits of plasma and spark ignition

In Fig.5, the rich limits of plasma jet ignition limits is less than that of spark ignition. When air flow rates is $20m^3/h$, the rich limits of plasma jet ignition limits reduces by 11.1%. When air flow rates is $72m^3/h$, the rich limits of plasma jet ignition limits reduces by 24.7%.

In Fig.5, the lean limits of plasma jet ignition limits of propane-air mixture is higher than that of spark ignition limits, and the gap between them became bigger with increasing air flow rates. When air flow rates is less than $20m^3/h$, the gap between them is very small, because the ignition is very easy under small air flow rates, and the advantage of applying plasma jet ignition is not obvious. At big air flow rates, flow field in the combustion chamber is very unstable, the ignition become difficult. Thus, the advantage of applying plasma jet ignition is obvious, and the lean limits of plasma jet ignition limits increase by 8.1% at air flow rates $100m^3/h$.

Continuing analysis of Fig.5, the ignition limits (the gap between rich and lean limits) extends with increasing air flow rates. Air flow rates at $100m^3/h$, arc current at 5.7A, the ignition limits of spark ignition is 2.71, the ignition limits of plasma jet ignition is 3.04, the ignition limits of propane-air mixture extends by 12.2%. The average ignition limits of spark ignition and plasma jet ignition are 2.34 and 2.57. The average ignition limits of propane-air mixture extends by 9.8%.

3.2 The influence of arc currents

To a certain plasma igniter, there are some effects which have important impact on ignition effect, such as the arc currents and argon flow rates. So it is necessary to investigate on them.

At argon flow rates 200L/h, arc currents 5.7A and 20.3A, air flow rates 0~$100m^3/h$, when we applied plasma jet ignition and spark ignition in the combustion chamber, the rich limits and lean limits of propane-air mixture are obtained (Fig.6).

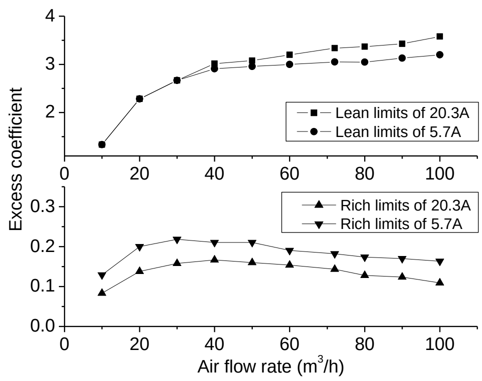

Fig.6 The ignition limits under different arc currents

In Fig.6, the rich limits reduces with increasing arc current. When air flow rates is $20m^3/h$, arc current 20.3A, the rich limits reduces by 27% than that of arc current 5.7A. At air flow rates $100m^3/h$, arc current 20.3A, the rich limits reduces by 33% than that of arc current 5.7A. The advantage of applying plasma jet ignition is obvious because the temperature of plasma jet increases with increasing arc current, and flow field in the combustion chamber is very unstable at bigger air flow rates. The higher the temperature of plasma jet is, the better ignition ability is, and the lower the rich limits is.

In Fig.6, the lean limits of propane-air mixture gradually increases with increasing arc current, and the gap between different arc currents become bigger with increasing air flow rates. When air flow rates is less than $30m^3/h$, the influence of arc current to the lean limits could be neglected. At air flow rates $100m^3/h$, arc current 20.3A, the lean limits increases by 8.7% than that of at arc current 5.7A.

Continuing analysis of Fig.6, the plasma jet ignition limits extends with increasing arc current, and the degree of extending plasma jet ignition limits increases with increasing air flow rates. The increase of arc current will cause the increase in the heating power of the arc on the argon stream, which can make the temperature of the argon rise. Depending on the gas state equation, the temperature rise will result in the expansion of gases. The density decreases; the volume and speed increase; part of the Internal energy is converted into kinetic energy. By increasing the flow velocity of the outlet, the torch length is increased so as to increase the ignition region. Thus, a improved ignition limits time is obtained. At air flow rates 100m^3/h, arc current 20.3A, ignition limits is 3.46, and extends by 13.8% than that of arc current 5.7A (3.04). The average ignition limits of 5.7A and 20.3A are 2.57 and 2.79. The average ignition limits of propane-air mixture extends by 8.5%.

3.3 The influence of argon flow rates

At argon flow rates 200L/h and 250L/h, arc current 20.3A, air flow rates 0~100m^3/h, when we applied plasma jet ignition in the combustion chamber, the rich limits and lean limits of ignition limits are obtained, which is shown in Fig.7.

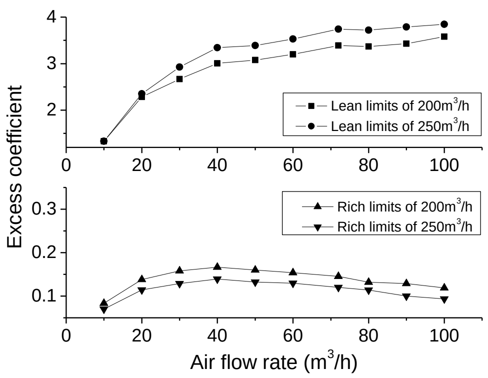

Fig.7 The ignition limits under different argon flow rates

In Fig.7, the rich limits increases first and then decreases with increasing air flow rates. When air flow rates 20m3/h, argon flow rates 200L/h, the rich limits is 0.138, argon flow rates 250L/h, the rich limits is 0.114, the rich limits reduces by 17.4%. When air flow rates 100m^3/h, argon flow rates 200L/h, the rich limits is 0.12, argon flow rates 250L/h, the rich limits is 0.09, the rich limits reduces by 25%. As the argon flow rates increases, the velocity of plasma jet increases with increasing air flow rates, the arc length becomes long, enhancing the arc’s penetrating ability and the rich limits reduces.

In Fig.7, the lean limits of propane-air mixture in the combustion chamber gradually increases with increasing air flow rates and argon flow rates, and the gap between different argon flow rates become bigger with increasing air flow rates. When air flow rates is less than 20m^3/h, the influence of arc current to the lean limits could be neglected. At air flow rates 100m^3/h, argon flow rates 250L/h, the lean limits increases by 10.6% than that of at argon flow rates 200L/h.

Continuing analysis of Fig.7, the plasma jet ignition limits extends with increasing argon flow rates, and the degree of extending plasma jet ignition limits improves with increasing air flow. At air flow rates 100m^3/h, argon flow rates 250L/h, plasma jet ignition limits is 3.86, and extended 11.6% than that at argon flow rates 200L/h (3.46). The average ignition limits of 200L/h and 250L/h are 2.79 and 3.08. The average ignition limits of propane-air mixture extends by 10.4%.

4. Conclusions

Plasma ignition technology is a new ignition methodology for combustion engines. Through the plasma jet ignition experiments, we investigated the ignition limits of plasma jet ignition and spark ignition. The influence of the arc current and argon flow rates of plasma igniter to ignition limits are also investigated. The results show that:

(1) The plasma jet ignition could extend the ignition limits of propane-air mixture obviously. The ignition limits extends with increasing air flow rates. The average ignition limits of spark ignition and plasma jet ignition are 2.34 and 2.57. The average ignition limits of propane-air mixture extends by 9.8%.

(2) The plasma jet ignition limits extends with increasing arc current, and the degree of extending plasma jet ignition limits increases with increasing air flow rates. The average ignition limits of 5.7A and 20.3A are 2.57 and 2.79. The average ignition limits of propane-air

mixture extends by 8.5%.

(3) The plasma jet ignition limits extends with increasing argon flow rates. The average ignition limits of 200L/h and 250L/h are 2.79 and 3.08. The average ignition limits of propane-air mixture extends by 10.4%.

Acknowledgements

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