Experimental investigation of flame characteristics in a lean-direct-injection spray combustor

Qinghua Zeng*,**, Yuhua Ai*, Chunjie Sui*,**, Wenjun Kong*a)
*Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing, 100190, China
**Graduate University of Chinese Academy of Sciences, Beijing, 100039, China

Summary A visual test combustor was established to investigate the flame characteristics of a lean-direct-injection (LDI) nozzle. The LDI nozzle was designed with a double-staged axial counter-swirl structure and a venturi-premixer. The flame characteristics including the flame length and flame colour were obtained. The results show that the flame length can be expressed by a formula of $L/D = 18.95 Fr^{2.27}(SMD/SMD_0)$.

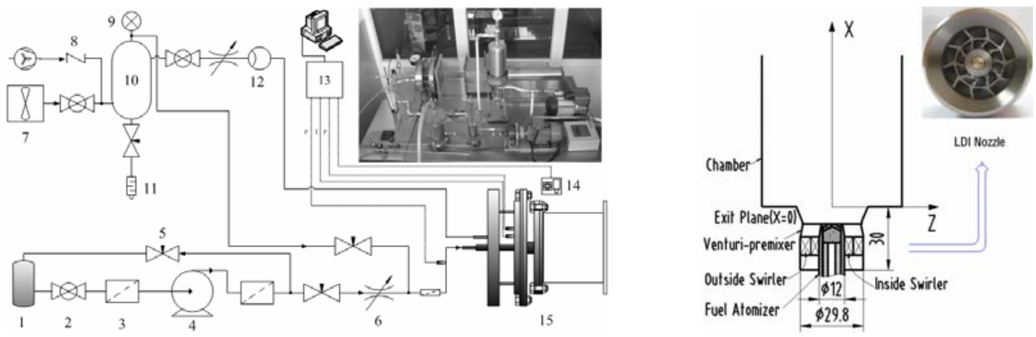
INTRODUCTION

Lean-direct-injection (LDI) is one of the inspiring technologies to reduce gas turbine combustion emissions. In this paper, the LDI nozzle was designed with a mechanical nozzle mounted in a central bore. Moving outward from the bore is a concentric air passageway. The air passageway is a double-staged axial counter-swirlers. In the downstream, the outer wall of the swirler is connected to a venturi-premixer. The outlet of the liquid fuel and the throat of the ventri-premixer are coplanar. The purpose of this structure is to get well atomization and mixing of the fuel and air quickly and uniformly. Using the LDI approach, the peak temperature throughout the flame can be reduced and thus the NOx-formation level is very low. Many investigations have shown that the NOx emissions from the LDI combustor are closed to those from the lean-premixed-prevaporized (LPP) combustion system [1,2]. Additionally, LDI combustor can avoid some problems encountered in LPP combustion, such as autoignition or flashback, and has the advantage of the stability of conventional combustors [1,3].

LDI nozzle based on axial single-swirl structure and venturi-premixer[4-6] was used mostly in LDI combustor at previous researches, and has some effects on the reduction of NOx emission. However, to greatly reduce the NOx emissions, it is necessary to further optimize the structure design. Another new LDI nozzle, based double-staged axial counter-swirl structure and venturi-premixer, investigated in this paper, is a kind of optimization design on basis of the single-swirl structure. In this paper, the flame characteristics of the LDI combustor based on the above new LDI nozzle are studied, and the results from the study will very important for the improvement of LDI combustor.

EXPERIMENTAL FACILITY

Fig.1 is the test system and schematic diagram of the LDI combustor. The test system consists of fuel supply system, air supply system and data acquisition and analysis system. The LDI combustor has a LDI nozzle and a rectangle chamber. The LDI nozzle contains three parts: a fuel atomizer, an double-staged axial counter-swirlers, and a venturi-premixer. The double-staged axial counter-swirlers is formed by the inside swirler and the outside swirler. The calculated swirl numbers of both the inside and outside swirlers are respectively 0.74 and 0.92. Swirling direction of the two swirlers is different. While the incoming air flows through the two swirlers, it will produce counter-swirl airflow at the exit plane. The chamber measure 200 mm x200 mm at square cross section and 200 mm in length. The flow rate of airflow is 31.97 kg/h and remains unchanged during the whole test. The NO.0 diesel is used and injected at different flow rates which in combination with the air flow rate respectively give different equivalence ratios of 0.33, 0.42, 0.48, 0.53, 0.59, 0.63.



(a) (b)

1-Tank 2-Ball Valve 3-Filter 4-Oil pump 5-Needle Valve 6-Regulating Valve 7-Air Pump 8-One-way Valve 9-Pressure Gage 10-Compensator 11-Silencer 12-Flowmeter 13-Data Acquisition 14-High Speed Camera System 15-LDI Combustor

Fig.1 Test system (a) and schematic diagram of the LDI combustor (b)

Corresponding author. Email: wjkong@mail.etp.ac.cn.

RESULTS AND DISCUSSION

Flame length at different equivalence ratios is shown in Fig.2. It is seen from Fig. 2, the flame length increased with the increase of the equivalence ratio. There is a change point with the equivalence ratio at about 0.55. For the equivalence ratio is less than 0.55, the flame length increased with the increase of the equivalence ratio, and the increase rate is gradually increasing. While the equivalence ratio greater than 0.55, the flame length also increased with the increase of the equivalence ratio, but the rate of increase tends to slow. The reasons of the above variation tendency are relation to the jet velocity of droplets, the heat exchange intensity between the droplets and environment, the diameter of droplets, and so on. As the equivalence ratio increases, the droplet jet velocity increases, then the penetrating ability of droplets and overall liquid spray distance of movement under the same turbulent air field also increase, thus the flame length increases. However, as the droplet velocity increases, the heat exchange between the droplets and environment will be also strengthened, and that will promote the evaporation of droplets, thus the increase of the flame length will be restricted. Additionally, on the equivalence ratio increase, the diameters of droplets are usually smaller, leading to the droplet evaporation easier, so this factor also affects the flame length increase. Considering the factors such as the droplet jet velocity, the droplets' diameter, an approximate formula for calculating LDI spray combustion flame length can be obtained.

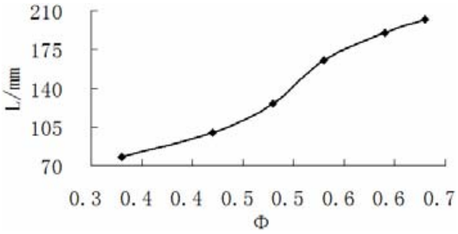


Fig.2 Flame length at different equivalence ratios

$$L/D = 18.95Fr^{2.27}(SMD/SMD_0),$$

where L is the flame length, D is the equivalent diameter of LDI nozzle, Fr is the Froude number, SMD is the Sauter-mean-diameter and the subscript 0 represents rated condition.

Fig.3 shows the evolution of the flame colour and surface at different equivalence ratios. Flame is bright when the value of equivalence ratio is small. As the equivalence ratio increases, the flame is gradually turning to yellow. At the equivalence ratio of 0.63, the flame becomes dark yellow. The study also finds that at lean equivalence ratios such as Φ=0.48, the root part of the flame, at the zone near the exit of LDI nozzle, is usually light blue. Which indicates the venturi-premixer has the ability to quickly mix the fuel and air. It is seen from Fig.3, the flame surface is smooth at small equivalence ratio. While at large equivalence ratio, the flame surface is unstable and wrinkling.

Φ=0.33 Φ=0.42 Φ=0.48 Φ=0.53 Φ=0.59 Φ=0.63

Fig.3 Evolution on flame colour and surface at different equivalence ratios

Fig.4 Enlarged view of the root flame at Φ=0.48

CONCLUSIONS

A visual test combustor was established to investigate the flame characteristics of a LDI nozzle. The LDI nozzle was designed with a double-staged axial counter-swirl structure and a venturi-premixer. The flame characteristics including the flame length and flame colour were obtained. The results show that the flame length increased with the increase of the equivalence ratio, and can be expressed by a formula of $L/D = 18.95Fr^{2.27}(SMD/SMD_0)$. Additionally, as the equivalence ratio increase, overall colour of flame is gradually from bright turning to yellow, and the flame surface gradually becomes unstable and wrinkling.

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