Experimental Study of the Effect of the Main Stage Stratifier Length on Flow Field and LBO Performance for a Lean Staged Injector

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ABSTRACT

The LBO performance of the pilot flame in a lean staged injector is studied in this work considering the influence of the main stratifier length. PIV and kerosene-PLIF experiments at non-reacting conditions were carried out to give an explanation of the difference in combustion performance. The evolution of spray and velocity in space is discussed in detail to find out the inherent correlations of combustion stability, fuel distribution and flow field. Moreover, special attention is paid to the PRZ changes as the stratifier length increases. Specifically, by lengthening the stratifier of the main stage, the PRZ is enlarged both axially and radially, and the LBO performances are improved accordingly. Then, the dominating mechanisms for the PRZ are pointed out that are responsible for the alteration of PRZ size.

INTRODUCTION

Due to the exponential increase of the air-traffic and the more and more stringent pollution control regulations, the reduction of pollution emission becomes the main goal of the research in aeronautical gas turbine (Lefebvre, 2010; Dunn-Rankin, 2008). Among the pollutants exhausted from engine, NOx is paid special attention, which not only contributes to the production of photo-chemical smog at ground level, but also cause damage to plant life and add to the problem of acid rain (Lefebvre, 2010). It is well-known that NOx is mainly generated in high temperature area, where the equivalence ratio is close to 1.0. Based on the correlation of NOx production rate with equivalence ratio, several innovative combustion concepts are invented and explored, such as LP (Lean Premixed), LPP (Lean Premixed Prevaporized), LDI (Lean Direct Injection) and RQL (Rich burn, Quick quench, Lean burn) (Foust, 2012). These combustion concepts enable combustion either in lean condition or rich initially and then lean. According to public available literatures, TAPS (Twin Annular Premixing Swirler) combustor, developed by GE Aviation and applied to GENx engine, can achieve a 70.5% reduction in NOx emissions relative to the ICAO CAEP/6 standard (Foust, 2012). Lean-burn fuel injector holds the highest potential for NOx reduction and can be expected to realize the -80% NOx reduction goal of ACARE (Lazik, 2008).

In the state-to-the-art designs that aim at achieving low emission, most of the combustion air is supplied and organized through the injector, especially for lean staged combustion. However, increasing the combustion air has a potential threat to operability and stability. In lean staged combustion, pilot stage is acknowledged as having the ability of improving the combustion stability, and attracts extensive attention from combustion researchers and engineers. Sulabh K. Dhanuka et al. (K. Dhanuka, 2009) experimentally...
investigated the mechanisms that caused a periodic combustion oscillation in pilot stage of TAPS injector through PLIF (Planar Laser Induced Fluorescence) and PIV (Particle Image Velocimetry) technique, and found that both PRZ (Primary Recirculation Zone) and LRZ (Lip Recirculation Zone) were beneficial for stable combustion, while the velocity gradients in the mixing layer were important in governing the stability of pilot flame. Later, James F. Driscoll and Jacob Temme (Driscoll, 2011) explored the interaction between PVC (Precessing Vortex Core) and recirculation zones that can be a source driving combustion instability. Further, they studied lean-limit combustion instability at elevated pressure, and concluded that the shear layer between main stage and pilot stage was responsible for the local extinction of pilot flame and the recirculated hot products can re-ignite the mixture prepared by pilot stage of the injector (K. Dhamuka, 2011). Cunxi Liu et al. (Cunxi Liu, 2016a; Cunxi Liu, 2016b) experimentally investigated the ignition and LBO (Lean Blow Out) performance by comparing two different pilot atomizer designs, and the results showed that matching pilot spray with swirling air streams was an effective method to improve combustion stability of the pilot stage of a fuel-staged multi-injection combustor. Wang B. et al. (Wang B., 2016; Kang Y., 2014) examined the effect of main swirler vane angle on ignition performance of a lean staged combustor, and they identified turbulence intensity and kerosene vapor distribution as the main causes for ignitibility difference.

In the above-mentioned literatures, pressure atomizer is used for the pilot stage fuel preparation. Recently some researchers use prefilm air blast atomizer to mix fuel with air efficiently which shows a perspective potential in emission reduction. Lazik et al. (Lazik, 2008) carried out ignition and lean blow out testing of the lean burn injector system with a pressure atomizer for pilot fuel atomization at atmospheric conditions, and the results showed that there was a trade-off between LBO AFRs (Air Fuel Ratio) and ignition performance with respect to swirl intensity. However, when replacing the pressure atomizer with a prefilm atomizer, the results showed a good potential for achieving excellent LBO performances with a reasonable ignition AFR. Antoshkiv et al. (Antoshkiv, 2008) examined the ignition characteristics of a lean burn injector system with the same pilot prefilm atomizer, the results illustrated that two possible spray and flame shapes determined different stability and ignition characteristics of the combustor. Later, Meier et al. (Meier, 2013) studied the soot formation in lean burn injector at pilot-only condition with LII (laser-induced incandescence) and PIV technique, and their findings would form the basis for developing strategies for smoke improvement at elevated pilot-only conditions. M. Kobayashi et al. (Kobayashi, 2011; Fujiwara, 2011) developed a lean staged combustion injector which utilized prefilm air blast atomization in the pilot stage. They researched the influence of different design parameters on ignition and LBO performance, and obtained the optimal value for these design parameters.

To the author's knowledge, few papers pay attention to the effect of flow field features on combustion stability of pilot flame under almost the same fuel distribution when prefilm atomizer is used for pilot stage fuel injection. In current investigation, the LBO performance of a lean staged injector is assessed experimentally and kerosene-PLIF and PIV diagnostics are used to clarify the correlation of lean combustion stability with recirculation zone structure and spray distribution. All test are carried out with the same pilot burner to obtain nearly identical spray pattern, and the length of the main stage stratifier is varied to alter the features of the main recirculation zone. Then, the combustion stability near LBO is correlated with flow structure and the critical mechanisms that play a important role in stable combustion are illustrated. Finally, the dominant factors that control the patterns of PRZ is analyzed, which can be used as a criterion for the optimization of the designed injector.

**EXPERIMENTAL APPARATUS**

1) The introduction of the lean staged injector

A schematic view of the fuel-staged lean staged fuel injector studied in this work is shown in Figure 1 which possesses the characteristics of stratified flame and partially premixed combustion. The lean staged injector comprises two part, namely the pilot stage and the main stage, corresponding to pilot flame zone and main flame zone in space respectively. The pilot stage is composed of two counter-rotating axial vane swirlers and a prefilm air blast atomizer. Pilot fuel supplied to the pilot stage first forms thin film at the trailing edge of the atomizer, then it is shorn by the counter-rotating swirling air through pilot stage swirlers and finally breaks into ligaments and droplets which mix with the pilot air streams. The main stage is located at the periphery of the pilot burner and introduces a uniform lean mixture of fuel and air into the dome region of combustor. Most of the air passing through the injector enters the main stage and is organized by the two swirlers of the main stage, namely the 3rd axial swirler and the 4th radial swirler, which is counter-rotating and separated by the main stage stratifier in space. The main fuel is introduced into the main swirler passage through multiple direct injection holes equally spaced on the inner surface of the 3rd swirler and impinges on the inner surface of the stratifier, which is expected to create fuel film and bursts into small droplets when interacting with the counter-rotating air streams. The outer swirler of the pilot stage and inner swirler of the main stage is co-rotating. The air split ratio between the pilot stage and the main stage is 6.5:1, while the air split ratio within each stage is 7:3. Only pilot burner is fuelled at the low power settings, such as idle and approach conditions. The pilot and main burner are both fuelled at some part and high power settings, such as climb and take-off conditions.

The effect of the stratifier length on the LBO performance as well as flow field and spray distribution is the main topic of the current work. The length of the main stage stratifier, which is illustrated in Figure 2 as H, is defined as the distance of the front wall of the fourth swirler to the trailing edge of the stratifier. Based on the difference of the stratifier length, three injectors, e.g., the baseline
injector, Injector A and Injector B, are investigated in this work. The non-dimensional stratifier length, H/D, for the three injectors are 0.065, 0.16, and 0.215 respectively, with D is the characteristic diameter of the lean staged injector.

2) Gas turbine model combustor facility

The isothermal and reacting experiments were conducted in the gas turbine model combustor facility in Institute of Engineering Thermophysics (IET), Chinese Academy of Science (CAS), as seen in Figure 3 (details can be seen in ref.(Cunxi Liu, 2016)). The tested combustor is installed within the outer casing of the test rig which can withstand the pressure difference of the inner and outer environments of the test facility. The transparent quartz window on the side of the combustor facility provides optical access for observations of the flame and laser diagnostics. The dilution air is independently supplied from the main air stream and is used for cooling the combustor liner as well as diluting the hot combustion products. In this study, the operating conditions (seen in Table 1) for isothermal and reacting experiments are at normal inlet temperature of 293.15 K and pressure of 1 atm. The overall pressure loss across the injector, fuel mass flow rate, and air mass flow rate are monitored in the experiments. The overall pressure loss of swirler $\frac{\Delta P_{sw}}{P_{3t}}$ defined as $(P_{3t} - P_{4t})/P_{3t}$ is measured by differential pressure transducer with an uncertainty of ±0.05%. The air mass flow rate is measured by orifice plate flow meter with an uncertainty of ±0.63%, while the fuel mass flow rate is measured by Corioils mass flow meter with an uncertainty of ±0.1%.

Only the pilot stage of fuel injectors work in the LBO experiments. During the LBO performance testing, the injector is initially ignited by spark igniter which is switched off as soon as stable combustion is attained. The boundary of lean blow out will be determined by gradually reducing the mass flow rate of pilot fuel until global extinction appears. The same test will be redone once to confirm the reliability of the test data.

3) Optical setup

The optical setup comprises of laser system, image capture and processing system, and controlling system, shown in Figure. 4. The laser system with sheet optics produces laser pulses having a duration of 8ns and a thickness of about 1 mm at a repetition rate of 15Hz. The laser is operated with a 2nd and 4th harmonic generator to produce pulse energy of 300mJ at 532nm and 25mJ at 266nm respectively. Double-excitation scheme with laser wavelength of 532nm and single-excitation scheme with laser wavelength of 266nm are used in PIV and Fuel-PLIF experiments respectively. The image capture system consists of image intensifier, CCD (Charge-couple Device) camera, lenses, interference band-pass and long-pass filters, used for obtaining the signal of desired wavelengths. The optical signals are detected with CCD camera perpendicular to the laser sheets. The camera is a 12-bit CCD with resolution of 1376×1024 pixels and framing rate of 10Hz. In PIV setup, CCD camera equips with Nikkor f=25mm lens and 532nm band-pass filter for detecting 532nm scattering signal. In Fuel-PLIF setup, CCD camera equips with image intensifier, UV Nikkor f=105mm lens, 266nm long-pass filters for
detecting the LIF signal. For fuel of RP-3 kerosene, the fluorescence signal with spectral band ranging from 270-420nm is red-shifted with respect to excitation laser wavelength, and the 266nm long-pass filter can be used to discriminate it from Mie scattered light. The gate width in the kerosene-PLIF experiments was set to 20ns. The whole system is controlled and synchronized by the PC via a PTU (Programmable Timing Unit) and the software, an intensified relay optics works together with PTU for setting variable exposure time and intensifier gain. For both the PIV and Fuel-PLIF measurements, the laser sheet is placed through the center of the combustor with the recording CCD camera placed normal to this plane.

The RP-3 kerosene is used both in the spray and combustion experiments. For the PIV measurements, the air is seeded with TiO2 particles, the seeded particles were nominally 3-5μm in diameter and about 4.2g/ccm3 in density. There is no fuel droplets in the PIV experiments.

The LBO performances are recorded as the FAR (Fuel Air Ratio) as soon as the pilot flame is globally extinguished, and it is plotted versus reference velocity, which is denoted as \( v_r \), and defined as the mean velocity across the plane of the maximum cross-sectional area in the combustor liner. Figure 5 makes a comparison of LBO performances of the three injectors with varied stratifier length. Owing to the baseline injector cannot be ignited successfully, no LBO data is acquired. It is observed in the igniting process of the baseline injector that the flame kernel can be generated around the igniter, then it is transported upstream by the recirculated air flow into the central zone rightly behind the pilot burner. This is in accord with the observation of reference (Wang B., 2016) which is captured by high speed camera. However, the pilot flame cannot anchor and stabilize in the pilot combustion zone, which is periodically extinguished and ignited. The two injectors with longer stratifier can be ignited successfully, and their LBO performances are illustrated in Figure 5. It can be seen from the results that the LBO performances are improved with the increase of the reference velocity, which is equivalent with raising the pressure drop across the combustor dome, and the Injector B outperforms Injector A in LBO performance. As the pilot fuel film is mainly atomized by the aerodynamic force of the pilot air stream, when the pressure drop across the injector decreases the atomization quality deteriorate substantially until the droplet size is so large that it cannot be effectively vaporized and mixed with combustion air, which plays an important role in affecting lean blow out. At constant overall swirler pressure drop \( \Delta P_{sw}/P_{3t} \), as the fuel mass flow is lowered, the fuel supply pressure is reduced to a threshold value below which the liquid film of the prefilm atomizer will be incontinuous, which influence the atomization uniformity of the spray and is susceptible to extinction.

In order to have a deep understanding of the mechanisms that induce lean blow out, the PIV and kerosene-PLIF experiments at isothermal condition are carried out to obtain details of flow field and kerosene spray distribution. The conditions selected for PIV and PLIF experiments are at overall injector pressure drop of 2%, 3%, and 4% respectively. The pilot fuel mass flow rate for PLIF experiments are 8kg/h and 18kg/h.

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**RESULTS AND DISCUSSION**

1) LBO performance tests

![Figure 5 The LBO performance of the lean staged injectors with different stratifier length](image)

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2) Spray distribution at isothermal conditions

![Figure 6 The spray distribution of the baseline injector at different \( \Delta P_{sw}/P_{3t} \) condition (\( \Delta P_{sw}/P_{3t} = 2\%, 3\%, 4\% \)) and fuel flow rate (\( m_f = 8kg/h, 18kg/h \))](image)
Figure 6 shows the time-averaged kerosene distributions of the baseline injector at the overall swirler pressure drop of 2%, 3%, 4% and pilot fuel mass flow rate of 8kg/h and 18kg/h, which are obtained by time-averaging of 100 raw fuel-PLIF images. The increase of pressure drop across the dome can enhance the aerodynamic interaction between fuel film and the shear layer generated by the tangential velocity gradients of the counter-rotating pilot air streams. Hence, the spread zone and angle of the spray is enlarged with the enhancement of the aerodynamic shear stress and this will result in more uniform fuel-air mixture and finer kerosene droplets, which in turn induces positive effect on stable combustion and LBO performances. Similarly, the increase of pilot fuel mass flow rate needs higher fuel supply pressure, which is beneficial for the initial breakup process and produces wider spray distribution with more fuel concentrating in the central zone just behind the injector. The concentration of spray around the center line is helpful for anchoring the pilot flame root as well as resisting flow unsteadiness.

Figure 7 is the comparison of spray distribution for injectors with varied stratifier length. It can be seen from the results that the distributions of fuel barely change with the increase of the length of main stage stratifier. The spray distribution of Injector B is slightly distinct from the other two cases with more uniform distribution of fuel and wider spread angle, which can be observed more clearly in the instantaneous image of the fuel distribution in Figure 8. The instantaneous fuel spray in the PLIF results of Injector B reaches the main stage outlet in radial direction and extends longer in downstream flow.

For the lean staged fuel injector studied in this work, the spray distribution and atomization are more sensitive to the aerodynamic interaction with the pilot air, and fuel supply pressure mainly affects the penetration distance. It seems the length of the main stage stratifier does not have much influence on spray distribution as far as this research is concerned.

Figure 8 The instantaneous spray image of lean staged injectors with different main stage stratifier length at \( \Delta P_{sw}/P_{3t} = 3\% \), and \( m_p = 8\text{kg/h}, 18\text{kg/h} \)

3) Flow field features at non-reacting condition

The flow field structure is obtained with PIV technique at non-reacting conditions for all the three injectors considered. The test condition includes the relative pressure drop of the swirler at 2%, 3%, 4%. As it is found by Liu CX et al. (Cunxi Liu, 2016), the pressure drop across the swirler has neglect influence on the flow field structure, so only the case of \( \Delta P_{sw}/P_{3t} = 3\% \) will be considered here. In Figure 9 the basic flow field features of Injector B at \( \Delta P_{sw}/P_{3t} = 3\% \) are illustrated in detail. It can be seen that there exists a huge PRZ which covers most area of the flow field, and the reversed air flows into the diffusion section of the pilot stage. The pilot air stream impinges with the reversed flow and is forced to flow in radial outside direction which is denoted as pilot air jet in Figure 9. No obvious LRZ and CRZ (Corner Recirculation Zone) is observed in the flow field images. The swirling air streams of the main stage eject out of the main stage at high velocity and the high speed rotation in the tangential direction will result in adverse pressure gradients which is the underlying reason for the formation of PRZ. The vortex core of the PRZ is also shown in Figure 9 for

Figure 9 The basic flow field features of Injector B at \( \Delta P_{sw}/P_{3t} = 3\% \)
comparing different cases of the stratifier length conveniently.

The influence of the stratifier length of the main stage is shown in Figure.10 together with the main features of the flow field. As the stratifier length increases, the position of the PRZ vortex core moves outwards and towards downstream, which demonstrates that the PRZ is enlarged in the radial and axial direction. This trend can be seen more clearly in Figure.11, where the axial and radial position of the vortex core is plotted vs non-dimensional stratifier length. As for the air jet of the main stage, when the stratifier is varied from the baseline injector to Injector A, the divergence angle of the air stream increases accordingly, so the confinement effect of the main air jet on PRZ is mitigated and the vortex core moves outwards. When it comes to Injector B, the divergence angle of the main air jet decrease a little relative to Injector A, however, it is still larger than the baseline injector. The convergence of the main air jet with respect to Injector A causes the vortex core to be blown downstream, during which the swirling intensity of the main stage is dissipated quickly and its confinement effect is further alleviated, so the vortex core moves even more outer in the radial direction.

To have a more clear understanding of the evolution of the velocity field in space, the axial and radial velocity components at three axial locations behind the injector, e.g. \(L=10\text{mm}, 20\text{mm}, 30\text{mm}\), are plotted against the radial distance to the centreline of the combustor. The velocity components are divided by the reference velocity to make the results more clear. As is shown in Figure.12, the axial velocity \(U\) and radial velocity \(V\) dissipate quickly as the air flows downstream. The width of the PRZ is indicated by the radial range where the axial velocity is below 0m/s. From the comparison of the axial velocity at the three axial locations, it is clear the width of the PRZ is enlarged with the increase of the stratifier length, which is in accordance with the analysis of Figure.10. Apart from that, the Injector B induce more intense reverse flow than the other two designs up to \(L=30\text{mm}\), which can be inferred from the axial velocity profile around the centerline of the combustor. We can also extract some important information from the axial velocity profile of the main stage air jet. As the stratifier is lengthened, the high speed zone of the main air jet becomes narrower and mainly covers the outer annular of the main stage outlet which is corresponding to the outer swirler of the main stage. Hence, it can be deduced reasonably that the PRZ of the baseline injector is mainly dominated by the pilot air stream and the main air streams from the 3rd and 4th swirler with opposite tangential velocity mix together with each other before it flow out of the main stage passage, so the main air streams confine the PRZ radially. Contrary to the baseline injector, the stratifier of injector B is longer and extends close to the outlet of the main stage, thus the two streams of the main air do not mix in time before they flow into the combustor. For Injector B, as the rotation direction of the 2nd swirler of the pilot stage is the same with the 3rd swirler of the main stage, the PRZ is jointly dominated by the pilot air stream and the inner air stream of the main stage, and the outer air stream of the main stage confines the PRZ and blows the vortex core downwards.
Figure 12 Radial profile of mean axial velocity and mean radial velocity at different axial locations (L=10mm, 20mm, 30mm) in central plane for isothermal condition (\(\Delta P_{sw}/P_{3t} = 3\%\)).

4) Correlation between flow field and LBO performances and the dominant mechanisms of recirculation zone

Moreover, the PRZ dominant mechanisms have been changed when the stratifier length is increased, as is demonstrated in Figure 13. For the baseline injector, the stratifier is shorter, so the counter-rotating air streams have enough time and space to dissipate each other and finally flow into the combustor with the same tangential velocity direction. Therefore, the PRZ is dominated by the pilot air stream and the main air stream affects the PRZ by confining the boundary of the PRZ under this circumstances. When it comes to Injector B, as the stratifier length increases, the mixing process of the main streams cannot be completed in the flow passage of the injector, leaving the inner air stream of the main stage rotates in the same direction with the pilot air stream. Under this condition, the PRZ is dominated by the pilot air stream and the inner air stream of the main stage together.

**CONCLUSIONS**

In current work, the influence of the length of the main stage stratifier on LBO performance is studied experimentally, and PIV and PLIF diagnostics are utilized to aid the understanding of the correlations between lean combustion stability, spray distribution and flow field features. The main conclusions include:

a) The enlargement of PRZ is beneficial for stable combustion and hence improve the LBO performance, which is resulted by the creation of appreciate velocity distribution for flame anchoring.

b) As the stratifier length increases, the PRZ controlling physics is changed from the pilot air stream dominant mechanism to the joint dominant mechanism of the pilot air stream and the inner air stream of the main stage.

**Nomenclature**

LBO: Lean Blow Out
LP: Lean Premixed
LPP: Lean Premixed Prevaporized
LDI: Lean Direct Injection
RQL: Rich burn, Quick quench, Lean burn
TAPS: Twin Annular Premixed Swirl Swirler
ACARE: Advisory Council for Aeronautics Research in Europe
PLIF: Planar Laser Induced Fluorescence
PIV: Particle Image Velocimetry
PRZ: Primary recirculation zone
LRZ: Lip Recirculation Zone
PVC: Precessing vortex core
AFR: Air fuel ratio
LII: Planar Laser-Induced Incandescence
CCD: Charge-couple Device
UV: Ultraviolet
PTU: Programmable Timing Unit
FAR: Fuel air ratio
H: The length of the stratifier length
D: The characteristic diameter of the lean staged injector
L: The distance behind the injector
L_{VC}: The axial or radial position of the vortex core
P_{3t}: Inlet total pressure of combustor
P_{4t}: Outlet total pressure of combustor
U: The axial velocity component
$V$: The radial velocity component

$\Delta P_{sw}$: Overall pressure drop across the swirler

$\Delta P_{sw}/P_3$: Overall pressure loss

$m_a$: The mass flow rate of air

$m_{fp}$: The mass flow rate of pilot fuel

$m_{fm}$: The mass flow rate of main fuel

$v_r$: The mean velocity across the plane of the maximum cross-sectional area of the casing in combustor

REFERENCES


