The mechanism analyses of key factors affecting operation range of a stratified partial premixed combustor

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ABSTRACT

The ignition and lean blow-out experiments of a stratified partial premixed combustor are carried out in a optical accessible single sector combustor. The flow field and spray pattern are obtained by laser diagnostic method to interpret the physical mechanism behind the combustion phenomena. The bottleneck factors are obtained for sub-phases in ignition and lean blow-out process.

INTRODUCTION

Increasingly stringent regulations on pollutant emissions, such as NOx, CO and soot, and improvement of engine thermodynamic performance, require to improve combustion efficiency and overall operability of kerosene-fuelled aeronautical gas turbines [1, 2]. Among key parameters likely to fulfill these goals, the injection system is one of them where substantial improvements can still be achieved. The new and innovative fuel injection concepts like LDI (Lean-Direction Injection), LP (Lean Premixed), and LPP (lean premixed prevaporized) have been proposed and improved [3-7]. The principle of these fuel injection strategies is to atomize the liquid fuel into small droplets which evaporate to a large extent, and mix the subsequent fuel vapor with air in a prevaporizing/premixing duct, in order to obtain a fairly homogeneous air/fuel mixture before combustion. In the development of low emission combustors for the next generation of aero-engines, lean-burn fuel injector utilising a significant amount of the air mass flow for fuel preparation and initiation of lean combustion holds the highest potential for NOx reduction and can be expected to the -80% NOx reduction goal of ACARE.

Over the latest 30 years, intensive research has been dedicated to improve lean-burn fuel injection systems and to imagine innovative designs in the field of aero-engine combustion for coping with operability and future regulations on pollution emissions. Antoshkiv et al. [8] examined the ignition characteristics of a lean burn injector system, the results illustrated that two possible spray and flame shapes determine different stability and ignition characteristics of the combustor. Lazik et al. [5] carried out ignition and lean blow-out testing of the lean burn injector system at atmospheric conditions, there is a trade-off between ignition and lean blow-out FAR for different swirl strength and configurations of pilot fuel injector. Later, Meier et al. [9] studied the effect of air/fuel ratio on soot formation during pilot-only operation of the lean burn injector system by planar laser-induced incandescence (LII), it was found that soot is formed predominantly in the upstream directed part of the shaped pilot flow near the interface to the outer main flow. Kobayashi et al. [10] investigated effects of swirler angle and swirler lip configurations on ignition performance of a lean staged burner, ignition performance was improved by extending heat shield to suppress the interaction of pilot flame and the main air stream, but other important performances of combustion were not evaluated. Lin et. al [11, 12] experimentally investigated the effects of igniter locations, flow number of pilot pressure swirl atomizer, step height and main swirl vane angle on ignition performance of a low emission stirred swirl combustor, the ignition process that the kernel propagates along the radial direction to the combustor center was obtained. Moreover, Sulabh et al. [13] investigated pilot flame structure of Twin Annular Premixed Swirler (TAPS) combustor by CH2O PLIF technique, the results illustrated that the pilot flame is subject to high strain rates present in the shear layer near the main annulus. Furthermore, Driscoll and Temme [14] explain why swirl has a strong stabilizing effect on flame in TAPS combustor.
Recently, Soworka et al. and Mastorakos [15] developed the code SPINTHIR to predict the ignition performance of a lean burn combustor, improvements on spray model and kernel formation are still underway. Despite the great number of publications dealing with swirling combustion, due to the extreme complexity of this system, there remains a lack of understanding for some of the physical mechanisms as well as less explored but still relevant areas of interest, such as correlation between flow field, spray characteristics and combustion performances. To the author’s knowledge, the bottleneck factors determining the operability of the fuel-staged combustor are still not clear, our work in this study will focus on this issue.

A pilot flame is key to the operability of the stratified partial premixed combustor with greater than 50% of the total combustor air flow premixed with the fuel before entering the reaction zone, the main flame cannot anchor without the presence of a pilot flame. A key research question motivating this study is mechanism analyses of bottleneck phase in ignition process and key factors leading to lean blow-out.

**EXPERIMENTAL SETUP**

**Fuel Injector**

A staged fuel injector of the stratified partial premixed combustor is developed in this study, seen in Fig.1. The fuel injector comprises two parts, namely the pilot stage and the main stage, corresponding to pilot flame and main flame in the stratified partial premixed combustor respectively. The pilot fuel nozzle in the center is a pre-filming air blast one and uses diffusion combustion, composed of two counter-rotating axial vane swirlers and a fuel prefilmer. The main fuel mixer using premixed combustion is set in a coaxial layout. Swirl of main stage is added by two sets of contrary swirl vanes. The main fuel is introduced into the main swirler passage through multiple direct injection holes equally spaced. 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 main fuel is injected in the middle and high engine power settings, such as cruise, climb and take-off conditions.

Three schemes of pilot fuel injector are used in this study to investigate the key factors affecting the ignition and lean blow-out performances. Compared with scheme A, the expansion section is removed in scheme B. The angles of inner swirlers of the pilot stage for scheme B1 and B2 are 40° and 0° respectively.

**Figure 1 Fuel injector of stratified partial premixed combustor**

**Single sector model combustor**

The isothermal and reacting experiments were conducted in a single sector model combustor in Institute of Engineering Thermophysics (IET), Chinese Academy of Science (CAS), as seen in Fig. 2. The transparent window on the side of the combustor facility provides optical access for observations of the flame. 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, fuel mass flow rate, and air mass flow rate are monitored in the experiments. The overall pressure loss of swirler defined as \((P_{31} - P_4)/P_{31}\) is measured by differential pressure transducer with an uncertainty of ±0.05%, the air mass flow rate is measured by orifice plate flow meter (Pipe diameter is \(D=100mm\), diameter ratio of orifice diameter to pipe diameter is \(\beta=0.60105\)) with an uncertainty of ±0.63%, the fuel mass flow rate is measured by Coriolis mass flow meter with an uncertainty of ±0.1%.

Only the pilot stage of fuel injectors works in the ignition and Lean Blow-out (LBO) experiments. The ignition test begins with a given Fuel Air Ratio (FAR), ignition data is obtained when three times of consecutive continued burning after the sparker has been switched off, the maximum time of sparking is 10 s, and the boundary of ignition test will be determined by gradually reducing the mass flow rate of pilot fuel until an unsuccessful ignition.
test. LBO data is obtained when flame went off during gradually reducing the fuel flow rate at a constant overall pressure loss of the swirler.

Figure 2 Stratified partial premixed model combustor

optical setup

The optical setup comprises of laser system, image capture and processing system, and controlling system, shown in Fig. 3. 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 wave length of 532nm and single-excitation scheme with laser wave length of 266nm are used in Particle Image Velocimetry (PIV) and Fuel Planar Laser Induced Fluorescence (Fuel-PLIF) experiments respectively. The image capture system consists of image intensifier, Charge-couple Device (CCD) camera, lenses, interference band-pass and long-pass filters, used for obtaining the signal of desired wavelengths. The optical signals were 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 50ns. The whole system is controlled and synchronized by the PC via a 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 Stokes number expressing the ability of the particle to track the flow is estimated by the ratio of the particle's characteristic settling time scale ($τ_p$) and characteristic time scale ($τ_f$) of flow,

$$St = \frac{τ_p}{τ_f} \quad (1)$$

$$τ_p = \frac{ρ_p d_p^2}{18 μ} \quad (2)$$

$$τ_f = \frac{10δ ΔU}{(3)}$$

where, $ρ_p$ is the particle density, $d_p$ is the particle diameter, $μ$ is the viscosity of air, $δ$ is the relevant length, $ΔU$ is velocity gradient. The highest velocities is on the order of 50m/s, taking $δ$ to be the smallest resolved length scale of 2.56mm. Based on equation (1), the Stokes number is about 0.05 (much less than 0.5 suggested by Clemens and Mungal [16]).

Figure 3 Optical setup

RESULTS AND DISCUSSION

Flow field

Figure 4 presents the mean velocity field of scheme B1 at relative pressure loss of 3%, 4% and 5% respectively. The results illustrate that the structure of flow field is the same at different relative pressure loss. The pilot and main recirculation zones overlap spatially. There is a big primary recirculation zone generated by the swirling air streams of both main and pilot stages. The magnitude of vectors at exit of the swirlers increases with relative pressure loss of the combustor.

Figure 4 Effect of relative pressure loss on mean velocity field (Scheme B1, isothermal)

The comparisons of mean flow field between scheme A, B1 and B2 are shown in Fig.5. The flow patterns of main
stage at the three case are the same. Both factor of expansion section and swirling angle of inner swirler of pilot stage lead to giant variation of pilot flow pattern. Firstly, the swirl of main stage predominates the formation of primary recirculation zone at case of scheme A, however, the primary recirculation zone is generated by the swirl of pilot and main stage jointly at case of scheme B1. The counter-rotating swirling air streams of inner and outer swirlers of pilot stage mix with each other in expansion section at case of scheme A, which weakens the swirling strength of pilot stage at exit of the fuel injector.

Compared the flow field of scheme B2 with B1, the variations of flow pattern of pilot stage leads to changing of axial velocity from negative to positive along the centerline. The high positive axial velocity all along the centerline destroys the primary recirculation zone. The interactions between air streams of pilot and main stage varies when changing of swirling angle of inner swirler of pilot stage from $45^\circ$ to $0^\circ$. In case of scheme B1, both swirl of pilot and main stage contribute to the generation of primary recirculation zone. However, in case of scheme B2, swirling air streams of main stage play a positive role in generating recirculation zone, while air streams of pilot stage play a passive role in generating recirculation zone. There are two vortices in the combustor, one of the vortices is generated by the swirling air streams of main stage, the other one is generated by interactions between recirculating air streams of main stage and pilot air streams with positive axial velocity.

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**Spray pattern**

The time-averaged results are obtained by time-averaging of 100 raw fuel-PLIF images in this study. The method of determining the spray cone angle of airblast fuel nozzle is shown in Fig.6. This is defined as spray cone angle in the dispersion region, which is formed between left and right border of the mass distribution in a spray image. As the border of spray is always a curve, two angles at two lines method can be used to compute spray angle. The top spray angle is defined between the atomizer exit plane and the first horizontal line, and the bottom spray angle is defined between the first and second horizontal lines. The top spray angle with $H_1=20\,\text{mm}$ is obtained in this study.

**Figure 5** Comparisons of mean flow field at pressure loss of 4% (isothermal)

**Figure 6** Method of determining spray cone angle for airblast fuel nozzle

The effects of relative pressure loss on spray pattern of B1 scheme with $m_{pf}=18\,\text{kg/h}$ are shown in Figure 7. The results illustrate that radial penetration of droplet increases with relative pressure loss on spray pattern. Hence, the fuel concentration increases at the zone near the igniter, which is beneficial to formation of flame core. Figure 8 presents the effects of fuel mass flow rate on spray pattern of scheme B1 at constant relative pressure loss of 3%. The results indicate that both the radial and axial penetration of droplets augment with increase of fuel mass flow rate.

**Figure 7** Effect of relative pressure loss on spray pattern (time-averaged, B1 scheme, $m_{pf}=18\,\text{kg/h}$, isothermal)

**Figure 8** Effect of fuel mass flow rate on spray pattern (time-averaged, B1 scheme, $m_{pf}=18\,\text{kg/h}$, isothermal)
The effects of relative pressure loss and fuel mass flow rate on spray pattern of B1 scheme are shown in Figure 9 and 10 respectively. The radial and axial penetration of droplets slightly increase with rising of relative pressure loss. However, the growing fuel mass flow rate leads to rapid increase of radial and axial penetration. Compared the spray pattern of scheme B2 with scheme B1, the non-swirling of inner swirler of pilot stage leads to collapse of pilot spray and substantially reduction of spray cone angle. Partial of droplets at the periphery of pilot spray are entrained by the recirculating air stream of main stage. Furthermore, the entrainment on pilot spray enhances with growing fuel mass flow rate. The entrainment on pilot spray increases the fuel concentration at zones near the igniter. However, at case of scheme B1, the recirculating main air streams entrains most of the droplets of pilot spray. Hence, the fuel concentration at zones near the igniter at case of scheme B1 is higher than at case of scheme B2.

The effects of relative pressure loss and fuel mass flow rate on spray cone of scheme B1 and scheme B2 are shown in Figure 11. The spray cone amplifies slightly with the increase of relative pressure loss and fuel mass flow rate at case of scheme B1. However, the spray cone amplifies rapidly with the increase of relative pressure loss and fuel mass flow rate at case of scheme B2. The spray cone at case of scheme B1 is always larger than that at case of scheme B2.

Figure 9 Effect of fuel mass flow rate on spray pattern (time-averaged, B2 scheme, \( m_{pf}=18kg/h \), isothermal)

Figure 10 Effect of fuel mass flow rate on spray pattern (time-averaged, B2 scheme, \( \Delta P_{sw}/P_{3t}=3\% \), isothermal)

The effects of relative pressure loss and fuel mass flow rate on spray cone of scheme B1 and scheme B2 are shown in Figure 11. The spray cone amplifies slightly with the increase of relative pressure loss and fuel mass flow rate at case of scheme B1. However, the spray cone amplifies rapidly with the increase of relative pressure loss and fuel mass flow rate at case of scheme B2. The spray cone at case of scheme B1 is always larger than that at case of scheme B2.

Figure 11 spray cone angle

(a) effects of relative pressure loss

(b) effects of fuel mass flow of pilot stage

Figure 12 illustrates the mean spray patterns of scheme A, B1 and B2. The three sprays are distinctive and representative respectively. The common spray features of scheme A and scheme B1 are good dispersion and penetration, high level of fuel concentration near the igniter. However, there is no fuel droplet in the center of the combustor at case of scheme A, while there is high level of fuel concentration in the center of the combustor at case of scheme B1. The common spray feature of scheme B1 and scheme B2 is high level of fuel concentration in the center of combustor. The distinctive spray features of scheme B2 are poor dispersion, penetration and low level of fuel concentration near the igniter.
Figure 12 Comparisons of spray pattern at condition of \( m_{pf} = 18 \text{kg/h} \) and \( \Delta P_{sw} / P_{3t} = 4\% \) (time-averaged, isothermal)

**Analyses of ignition and LBO performances**

The stratified partial premixed combustor with scheme A can not be ignited at relative pressure loss of 2.0\% to 5\%. The ignition and lean blow-out combustion performances at relative pressure loss of 2.0\% to 5\% are shown in Fig. 13. The results illustrate that the ignition and lean blow-out performances are greatly improved at case of scheme B1, compared with the results of scheme B2.

**Analysis of ignition and LBO process**

According to lefebvre's understanding of gas turbine ignition, there are two distinct phases in ignition process in a single sector model combustor. Phase 1 is the formation of a flame kernel of sufficient size and temperature to be capable of propagation. Phase 2 is the subsequent flame propagation from this kernel to the primary zone. For the stratified partial premixed combustor, the pilot fuel works singly at igniting condition, the phase 2 is the propagation of flame kernel to the pilot zone. Basing on the results of flow field in Fig.5, spray pattern in Fig.12 and ignition performances in Fig. 13, the analyses of bottleneck factors in ignition process are carried out.

Comparing the flow field and spray pattern of scheme A and B1, the size of primary recirculation zone and flow field at this two cases are similar. Hence, the variation of spray between scheme A and B1 induces the changing of ignition performances. According to sub-phases in ignition process, the flame kernel can be formed in phase 1 as there is a high level of fuel concentration near the igniter, the propagation of flame kernel to the pilot zone in phase 2 can come into being as the whole spray is in primary recirculation zone. The fact is that the stratified partial premixed combustor with scheme A can not be successfully ignited. Hence, a new phase (phase 3) that the process of anchoring of pilot flame in the center of the combustor should be added. No droplet in the center of the combustor at case of scheme A gives rise to failure of ignition. Based on the above analyses, the spatial distribution of droplet in spray is the key factor determining the ignition performance of scheme A and B1.

Comparing the flow field and spray pattern of scheme B1 and B2, the inner swirl angle has a great impact on both flow field and pilot spray pattern. In the phase 1 of ignition process, the low level of fuel concentration near the igniter goes against the formation of flame kernel. In the phase 3 of ignition process, the high level of fuel concentration in the center of combustor is beneficial to the anchoring of pilot flame, while the positive axial velocity of pilot stage is to the disadvantage of pilot flame anchoring. Hence, the spray pattern and flow field of pilot stage both are key factors determining the ignition performance.

Concerning the lean blow-out performances, the high level of fuel concentration in the center of combustor of scheme B2 is beneficial to the anchoring of pilot flame, while the positive axial velocity of pilot stage leading to the lift-off of pilot flame (seen in Fig.13) is to the disadvantage of pilot flame anchoring. The results that both the ignition and lean blow-out performances of scheme B2 are worse than that of scheme B1, illustrate that adverse effects of positive axial velocity on flame anchoring in the pilot stage at case of scheme of B2 predominates the beneficial effects of high fuel concentration on pilot flame anchoring.
CONCLUSIONS

The analyses of bottleneck factors affecting the ignition and lean blow-out of a stratified partial premixed combustor are carried out in this study. For ignition process in a single sector combustor, a new phase that the anchoring of pilot flame in the center of the combustor should be added. At case of scheme A, the spray pattern that there is no fuel in the center of the combustor is the bottleneck factor for ignition process, as the pilot flame can not anchor in ignition process. At case of scheme B2, the phase 1 (formation of flame kernel) is the bottleneck in ignition process, because the spray pattern with low concentration near the igniter leads to reduction of probability of formation of flame kernel. The variation of passive axial velocity in the center of combustor at case of scheme B1 to positive axial velocity in the center of combustor at case of scheme B2 induces the lift-off of pilot flame and then lean blow-out. The best operability is obtained for scheme B1 for this stratified partial premixed combustor.

NOMENCLATURE

LBO: Lean Blow-out
Fuel-PLIF: Fuel Planar Laser Induced Fluorescence
PIV: Particle Image Velocimetry
UV: Ultraviolet
PTU: Programmable Timing Unit
PLI: Planar Laser-Induced Incandescence
LP: Lean Premixed
LPP: Lean Prevaporized Premixed
LDI: Lean Direct Injection
ACARE: Advisory Council for Aeronautics Research in Europe
CCD: Charge-couple Device
CO: Carbon Monoxide
NOx: Oxides of nitrogen
UHC: Unburned Hydrocarbons
TAPS: Twin Annular Premixed Swirler
PRZ: pilot recirculation zone
MRZ: main recirculation zone
LRZ: Lip Recirculation Zone
CRZ: Corner Recirculation Zone
SMD: Sauter mean diameter
FAR: Fuel air ratio
Φ: Equivalence ratio
ΔPf: Pressure differential of fuel
P3t: Inlet overall pressure of combustor
ΔPsW: Overall pressure drop across the swirler
ΔPsw/P3t: Overall pressure loss
vrf: The mean velocity across the plane of the maximum cross-sectional area of the casing in combustor
D: Pipe diameter of orifice plate flow meter
β: Diameter ratio of orifice diameter to pipe diameter
St: Stokes number
τp: Characteristic settling time scale of particle
τλ: Characteristic time scale of flow
ρp: Particle density
dp: Particle diameter
µ: Viscosity of air
δ: Relevant length
ΔU: velocity gradient.

ACKNOWLEDGEMENTS

This work was supported by National Natural Science Foundation of China with project No. 51406202. The support is gratefully acknowledged.

REFERENCES


