engineering proceedings

MDPI

Proceeding Paper

Computational study of the effect of dual air swirling injection on turbulent combustion of kerosene-air at a high pressure †

Dongxin Huang [1,2], Danyang Wang [1], Jianguo Xu [1] and Hua Meng [1,*]

[1] School of Aeronautics and Astronautics, Zhejiang University, Hangzhou, Zhejiang 310027, China
[2] Zhejiang Development & Planning Institute, Hangzhou, Zhejiang 310012, China
* Correspondence: menghua@zju.edu.cn
† Presented at the title, place, and date.

Abstract: The air compression ratio in a modern aero engine has been significantly increased to enhance the engine's thermal efficiency, thereby leading to high-pressure combustion with the combustor pressure exceeding the fuel's critical pressure (~23 atm for the aviation kerosene). In this work, large eddy simulations are conducted to investigate the effect of two air swirling injection on flow dynamics and turbulent combustion of kerosene-air in a dual-swirl model combustor at a supercritical pressure of 4 MPa. The flamelet progress-variable (FPV) model is applied to handle turbulent/chemistry interaction, and the extended corresponding states (ECS) method is adopted to evaluate thermophysical property variations. Results indicate that the inner air swirler controls flow and chemical reactions inside the injector, while the outer air swirler exerts strong impact on flow and flame characteristics in the combustor. A precessing vortex core (PVC) is generated by the inner swirling flow, and its frequency increases significantly as the inner air swirler angle varies from 25° to 40°. A modified Strouhal number is proposed for PVC frequency analyses, which reveal that the PVC frequency is influenced by the inner swirl number and the maximum axial velocity in the inner injector. Results obtained herein would help gain fundamental understanding on swirling flow and flame dynamics at high pressures.

Keywords: Gas turbine combustor; Large eddy simulation; Swirl number; PVC frequency; Strouhal number.

1. Introduction

A modern gas turbine engine is the highly efficient and reliable power plant employed in the aviation system. The engine's compression ratio has been increased constantly, reaching more than 40 [1], to improve its thermal efficiency [2]. This would result in high-pressure combustion at high-thrust conditions, with the chamber pressure above the critical pressure of the aviation fuel, which is at around 23 atm.

Swirling air injection is commonly implemented in a gas turbine engine to enhance fuel-air mixing and flame stability [3], and therefore, the swirler angle exerts direct impact on fluid flows and flame dynamics in the engine combustor [4-6]. Many researchers have investigated the effect of air swirlers on turbulent flow and combustion in gas turbine engines. Huang et al. [7] conducted large eddy simulations in a lean-premixed swirl-stabilized combustor with a single set of axial swirler vanes and analyze the effect of inlet swirling flow on turbulence intensity and flame speed. Li et al. [8] and Aliyu et al. [9] analyzed the effect of swirl number on flow dynamics and flame characteristics in a gas turbine model combustor. Wang et al. [10] studied the influence of multiple sets of air swirlers on vortical flow dynamics in a gas turbine injector and discussed the unsteady motion with different inlet swirling intensities.

Citation: To be added by editorial staff during production.

Academic Editor: Firstname Lastname

Published: date

As the combustion chamber pressure in a modern aero engine becomes higher than the fuel's critical pressure, the supercritical-pressure fuel injection, mixing, and combustion processes show different characteristics from those at a low-pressure. At a supercritical pressure, the surface tension of the fuel significantly decreases, and its heat of vaporization vanishes. Consequently, the fuel-air mixing and combustion processes are controlled directly by turbulent flows, with large variations of thermophysical properties [11]. A supercritical-pressure turbulent combustion model has recently been introduced for studying swirling flow and combustion in an aero engine model combustor at various chamber pressures and fuel-air equivalence ratios [6].

Large eddy simulations are further conducted in this paper to study the effect of dual air swirling injection on swirling flow and turbulent combustion of the aviation kerosene and air in a dual-swirl model combustor at a high pressure of 4 MPa. This work focuses on analyzing the interactions of two air swirlers, with varied swirler angles, on high-pressure flow dynamics and flame characteristics in an aero engine combustor.

2. Numerical method

A recently-developed high-pressure turbulent combustion model [6], based on the flamelet progress-variable (FPV) approach [12] with consideration of the general-fluid effect, is applied in the present numerical study.

In this model, laminar counterflow flames are calculated using the flamelet equations, and the flame databases are generated using the presumed shape PDFs. Large thermophysical property variations are evaluated using the extended corresponding states (ECS) method, based on the accurate properties of a reference fluid, propane [13,14]. A three-component surrogate model, which consists of 74% n-decane, 15% n-propylbenzene, and 11% n-propylcyclohexane in volume, is used to represent the aviation kerosene. A detailed chemical reaction mechanism, containing 209 species and 1673 elementary reactions, is applied to handle chemical reactions [15].

Model validations have been conducted in the prior publications [6,16]. Numerical results have shown good agreements with experimental data from both the swirling combustion in a dual swirl model combustor at the atmospheric pressure and from the coaxial combustion in a model rocket combustor at a high pressure of 5.6 MPa. Details regarding the numerical model, computational set-up, and model validations can be found in the reference [6] and its enclosed supplementary data.

3. Results and discussion

In this work, large eddy simulations have been further conducted to analyze the effect of two varied air swirler angles on swirling flow and turbulent combustion of the aviation kerosene and air in a dual-swirl gas turbine model combustor at a high pressure of 4MPa. Fig.1(a) shows the schematic of the combustor, which is chosen, with slight modification, from the work by Chrigui et al [17]. It consists of a cylindrical domain of 150 mm in length and 96 mm in diameter, and a contracted exit section of 40 mm in diameter. Fig. 1(b) illustrates the injection system, which contains two radial air swirlers and a fuel nozzle with a diameter of 1 mm. The mean exit angles of the inner and outer swirlers are defined by α and β, respectively, as shown in Fig. 1(b). In the present work, two inner swirler angles, 40° and 25°, combined with two outer swirler angles, 45° and 30°, are studied. The mass flow rates of the fuel, inner swirling air, and outer swirling air are 17.96, 141.44, and 212.16 g/s, respectively, maintaining an overall fuel-air equivalence ratio at a lean condition of 0.75. The fuel is injected at a temperature of 300 K, while the air at an increased temperature of 860 K, due to the compression-related heating. The other relevant parameters can be found in the references [6,17].

According to grid-independence studies [6], a set of computational meshes of 4.4 million hexahedral cells, which are sufficiently refined in the injector and flame regions, are used in the present large eddy simulations. In the calculations, the computational time step is set at 0.5 μs to ensure the maximum CFL number less than 1.0. The statistical results are collected after 10 flow-through time with over 30 ms.

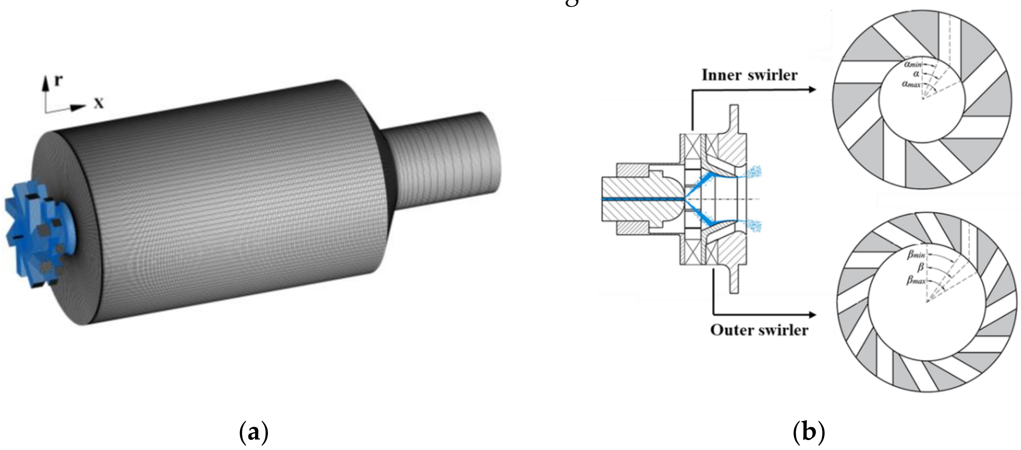

Figure 1. Schematics of (**a**) the model combustor and (**b**) the dual-swirler injection system

3.1. Effect of the inner air swirler

The effect of the inner air swirler angle on swirling flow and combustion is first calculated and analyzed.

Figs.2a and 2b show the time-averaged axial velocity variations, with the inner swirler angle (α) varied from 25° to 40° and the outer swirler angle (β) fixed at 45°. At an inner swirler angle of 25° (Fig.2b), a U-shaped central recirculation zone (CRZ) can be observed in the main combustor. As the swirler angle increases to 40° (Fig.2a), however, the CRZ extends upstream inside the inner injector, leading to a Y shape.

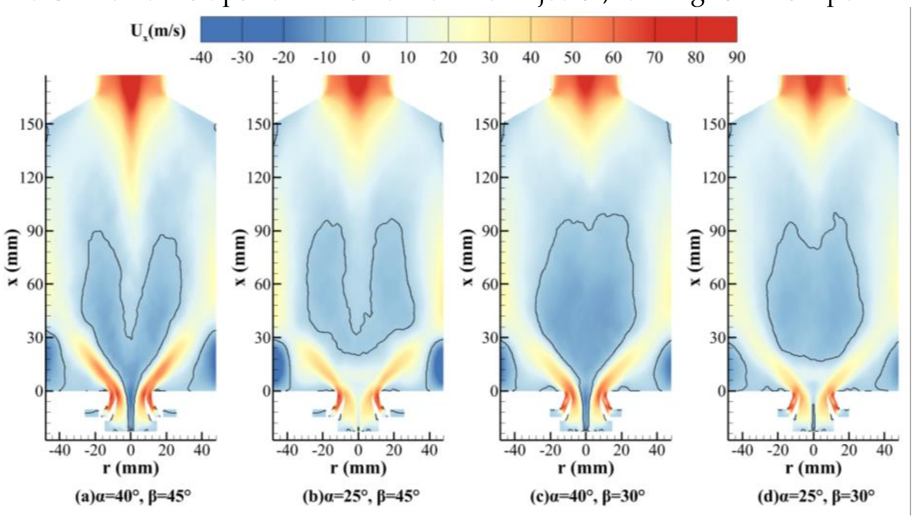

Figure 2. Variations of the time-averaged axial velocity (the black line denotes the location at zero velocity)

The swirling air injection exerts strong impact on turbulent combustion. Figs.3a and 3b show the time-averaged temperature variations. At a larger inner swirler angle of 40° (Fig.3a), the stronger recirculating flow carries the hot combustion products back into and thus cause chemical reactions inside the inner injector. In the case at α=25° (Fig.3b), however, combustion and the flame exist only at the injector exit.

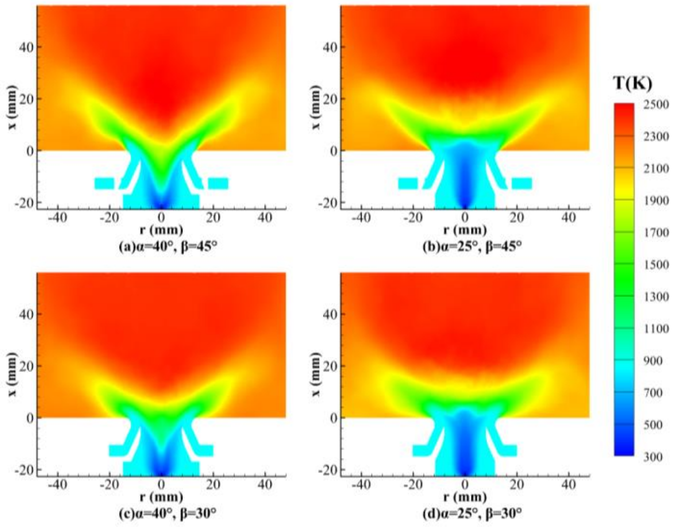

Figure 3. Variations of the time-averaged temperature

The strong swirling flow generates a precessing vortex core (PVC), which originates in the inner injector [6]. The PVC-related flow oscillation is monitored and recorded at a location in the combustor with x = 11 mm and r = 12 mm (x=0 defined at the injector exit). Fast Fourier Transformation (FFT) is performed to obtain the oscillating frequencies. The main PVC frequency (*f*), as listed in Table 1, increases from 994 to 1736 Hz, as the inner air swirler angle increases from 25° to 40°, at an outer swirler angle of 45°.

In this work, a modified Strouhal number, Sr_c, is introduced for PVC frequency analyses.

$$Sr_c = \frac{f\, d_{inner}}{u_{max}} \tag{1}$$

where d_{inner} is the inner injector diameter, u_{max} the maximum axial velocity in the inner injector.

Calculations demonstrate that the modified Strouhal number, Sr_c, is essentially proportional to the inner swirl number, as confirmed by the following relationship:

$$SC = \frac{Sr_c}{S_{inner}} = \frac{f \cdot d_{inner}}{S_{inner} \cdot u_{max}} \tag{2}$$

where the S_{inner} is the inner swirl number, defined as the ratio of the angular momentum flux to the axial momentum flux.

As listed in Table 1, the calculated parameter, *SC*, is approximately a constant at around 0.8 for the two studied cases, with a relative difference less than 5%. This indicates that the PVC frequency is controlled mainly by the inner swirl number and the maximum axial velocity in the inner injector (Eqn.2). Therefore, at a larger inner swirler angle of α=40°, the combined effects of the increased inner swirl number and the local flow acceleration in the inner injector result in the increased PVC frequency (the PVC frequencies are presented in Table 1).

Table 1. The modified Strouhal numbers and PVC frequencies

Outer swirler angle (α)	**45°**		**30°**	
Inner swirler angle (β)	**40°**	**25°**	**40°**	**25°**
Inner swirl number S_{inner}	0.556	0.448	0.613	0.449
Maximum axial velocity u_{max} (m/s)	63.8	43.5	60.6	52.1
PVC frequency (Hz)	1736	994	1763	1189
Sr_c	0.435	0.366	0.465	0.354
SC	0.783	0.816	0.759	0.813

3.2. Effect of the outer air swirler

The effect of the outer air swirler angle is also investigated. The outer air swirler angle varies from β=45° to 30°, with the inner swirler angle fixed at 40° or 25°.

At α=40°, the time-averaged axial velocity distributions for two different β angles are presented in Figs.2a and 2c. For both cases, strong recirculation flow can be observed inside the inner injector. At the outer swirler angle of β=30°, the CRZ in the combustor changes to a bubble shape. This indicates that flow acceleration in the downstream region of the combustor is significantly weakened, as the outer swirler angle decreases.

At α=25°, flow fields at the two different β angles are shown in Fig.2b and 2d. For both cases, the reverse flow in the inner injector disappears. A bubble-shaped CRZ can again be observed in the combustor at the outer swirler angle of β=30°. Results in Fig.2 clearly demonstrate the strong impact of the outer swirler on the recirculating flow in the combustor.

Figs.3a and 3c present the time-averaged temperature variations at the two different outer swirler (β) angles, at α=40°. Combustion occurs inside the inner injector in both cases, but at β=45°, flame moves slightly upstream. Figs.3b and 3d illustrate the temperature distributions at the two different β angles, at α=25°. Results show improved flame holding capability at an increased outer swirler angle of β=45°.

The PVC-related parameters at two different outer swirler angles can also be found in Table 1. At α=40°, the PVC frequencies are approximately the same at the two different outer swirler angles. This is attributed to a balance between the varied inner swirl number and the varied maximum axial velocity. At a moderate inner swirler angle of α=25°, however, the PVC frequency increases from 994 to 1189Hz, as the outer swirler angle (β) decreases from 45° to 30°. This is due mainly to the increased maximum axial velocity in the inner injector.

It is notable that the parameter, SC, remains essentially a constant in all of the four cases listed in Table 1, with a maximum relative error within 7%.

4. Conclusions

Large eddy simulations are conducted in this work to investigate the swirling injection and combustion of kerosene-air in a dual-swirl model combustor at a high pressure of 4MPa, above the critical pressure of kerosene. This work focuses on analyzing the effect of dual air swirling injection, with varied swirler angles, on high-pressure flow and combustion characteristics.

Results indicate that the inner air swirler controls the mixing process and chemical reactions inside the injector, and increasing the inner swirler angle would induce recirculating flow and combustion inside the injector. The outer air swirler exerts strong impact on flow and flame characteristics in the combustor. As the outer swirler angle decreases, the central recirculation zone in the combustor changes into a bubble shape, owing to weakened flow acceleration in the downstream region of the combustor.

A precessing vortex core (PVC) is generated by the inner air swirling injection, with the PVC frequency increasing significantly as the inner swirler angle increases from 25° to 40°. Changing the outer swirler angle, from 45° to 30°, makes only weak effect on the PVC frequency. At a moderate inner air swirler angle of 25°, the PVC frequency increases as the outer air swirler angle decreses.

A modified Strouhal number is proposed in this work, and the detailed analyses of the Strouhal number indicate that the PVC frequency is controlled mainly by the inner swirl number and the maximum axial velocity in the inner injector.

Author Contributions: Conceptualization, H.M.; methodology, H.M.; software, D.H., D.W. and J.X.; validation, D.H., D.W. and J.X.; formal analysis, D.H. and J.X.; investigation, D.H.; writing—original draft preparation, D.H. and D.W.; writing—review and editing, H.M.; visualization, D.H., D.W. and J.X.; supervision, H.M.; project administration, H.M.; funding acquisition, H.M.

Funding: National Natural Science Foundation of China (12072321) and National Science and Technology Major Project (2017-III-0005-0030).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author

Acknowledgments: This work was financially supported by the National Natural Science Foundation of China (12072321) and the National Science and Technology Major Project (2017-III-0005-0030).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Epstein, A.H. Aircraft engines' needs from combustion science and engineering. *Combustion and Flame* **2012**, *159*, 1791-1792.
2. Saravanamuttoo, H.I.H.; Rogers, G.F.C.; Cohen, H. *Gas turbine theory*; Pearson education: 2001.
3. Lefebvre, A.H. *Gas Turbine Combustion*; CRC Press: 1998.
4. Syred, N. A review of oscillation mechanisms and the role of the precessing vortex core (PVC) in swirl combustion systems. *Progress in Energy and Combustion Science* **2006**, *32*, 93-161.
5. Gicquel, L.Y.M.; Staffelbach, G.; Poinsot, T. Large Eddy Simulations of gaseous flames in gas turbine combustion chambers. *Progress in Energy and Combustion Science* **2012**, *38*, 782-817.
6. Huang, D.; Xu, J.; Chen, R.; Meng, H. Large eddy simulations of turbulent combustion of kerosene-air in a dual swirl gas turbine model combustor at high pressures. *Fuel* **2020**, *282*, 118820.
7. Huang, Y.; Yang, V. Effect of swirl on combustion dynamics in a lean-premixed swirl-stabilized combustor. *Proceedings of the combustion institute* **2005**, *30*, 1775-1782.
8. Li, S.; Zheng, Y.; Zhu, M.; Martinez, D.M.; Jiang, X. Large-eddy simulation of flow and combustion dynamics in a lean partially premixed swirling combustor. *Journal of the Energy Institute* **2017**, *90*, 120-131.
9. Aliyu, M.; Nemitallah, M.A.; Said, S.A.; Habib, M.A. Characteristics of H2-enriched CH4O2 diffusion flames in a swirl-stabilized gas turbine combustor: Experimental and numerical study. *International Journal of Hydrogen Energy* **2016**, *41*, 20418-20432.
10. Wang, S.; Hsieh, S.-Y.; Yang, V. Unsteady flow evolution in swirl injector with radial entry. I. Stationary conditions. *Physics of fluids* **2005**, *17*, 045106.
11. Yang, V. Modeling of supercritical vaporization, mixing, and combustion processes in liquid-fueled propulsion systems. *Proceedings of the Combustion Institute* **2000**, *28*, 925-942.
12. Pierce, C.D.; Moin, P. Progress-variable approach for large-eddy simulation of non-premixed turbulent combustion. *Journal of Fluid Mechanics* **2004**, *504*, 73-97.
13. Meng, H.; Yang, V. A unified treatment of general fluid thermodynamics and its application to a preconditioning scheme. *Journal of Computational Physics* **2003**, *189*, 277-304.
14. Xu, K.; Meng, H. Analyses of surrogate models for calculating thermophysical properties of aviation kerosene RP-3 at supercritical pressures. *Science China Technological Sciences* **2015**, *58*, 510-518.
15. Dagaut, P.; Cathonnet, M. The ignition, oxidation, and combustion of kerosene: A review of experimental and kinetic modeling. *Progress in Energy and Combustion Science* **2006**, *32*, 48-92.
16. Huang, D.; Wang, Q.; Meng, H. Modeling of supercritical-pressure turbulent combustion of hydrocarbon fuels using a modified flamelet-progress-variable approach. *Applied Thermal Engineering* **2017**, *119*, 472-480.
17. Chrigui, M.; Sadiki, A.; Janicka, J.; Hage, M.; Dreizler, A. Experimental and numerical analysis of spray dispersion and evaporation in a combustion chamber. *Atomization and Sprays* **2009**, *19*, 929-955.