Large-eddy simulation of flow and combustion dynamics in a lean partially-premixed swirling combustor

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Abstract

A lean partially premixed swirling combustor is studied by resolving the complete flow path from the swirl vanes to the chamber outlet with large-eddy simulation (LES). Flow and combustion dynamics for non-reacting and reacting situations are analysed. The influence of Reynolds number on the vorticity distribution and vortex rings formation for non-reacting cases is examined. A modified flame index is introduced to identify the flame regime during the partially premixed combustion. The combustion instability phenomenon is detected by applying Fourier spectra analysis. Several scalar variables are monitored to investigate the combustion dynamics at different operating conditions. The effects of swirl number, equivalence ratio and nitrogen dilution on combustion dynamics are studied in detail.

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1. Introduction

Lean premixed (LP) combustion is a promising technology used in gas turbine engines for reducing both NOx emissions as well as reaction zone size. To obtain optimal fuel/air mixing at the combustor inlet and avoid combustion instability, swirling injectors are typically used in gas turbine systems to provide the desired fuel/air distribution and produce central toroidal recirculation zones (CTRZs), which serve as the dominant flame stabilization mechanism. However, vortices breakdown due to swirl flows may cause flow motion instability and combustion oscillation. Many works have been conducted to study the influence of intrinsic swirling flow and operating conditions on flow and combustion dynamics [1].

Although valuable information has been obtained by these studies, there are still many unresolved issues regarding flame dynamics, the mechanisms of flame/vortex interactions in swirl lean premixed combustors, which require further investigation. In the present work, a swirl-stabilized lean-premixed natural gas combustor in our experiment is simulated using a parallel LES method to examine the influence of different operating conditions on flow and flame dynamics. The theoretical formulation and numerical methods are given in section 2. Results are discussed in section 3 and a conclusion is given in section 4.

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2. Theoretical formulation and numerical methods

The schematic diagram of the experimental combustor is shown in Fig. 1. The combustor consists of a 52-degree, eight spiral swirl-vaned air inlet with a swirl number 0.9 and five column fuel injectors located downstream of the vanes, followed by an annular chamber. Air and fuel are injected in opposite directions and premixed inside a short passage before combustion takes place in the chamber. The swirl structure and column injector are shown in Fig. 2a and 2b, respectively. The filtered LES equations for unsteady, reacting, multi-species flow are solved in the present work. The detail of the mathematical formulation could refer to [2]. The unclosed subgrid terms are modelled by gradient assumption and the eddy-viscosity concept method. The eddy dissipation concept (EDC) model based on finite-rate chemical reaction is employed to represent the flame-turbulence interaction. An empirical three-step reduced methane reaction mechanism is employed in the present study [3]. Experiments conducted by Griebel et al. [4] are used to validate the reduced reaction mechanism. Comparative results of the flame front and axial velocity field between the numerical simulation and experiment are shown in Fig. 3. Good agreement is obtained, which demonstrates that the three-step reduced mechanism can be applied with reasonable accuracy to the study of natural gas combustion in our cases. The computational fluid dynamics modelling program is based on KIVA-4 code, in which the Arbitrary Lagrangian Eulerian (ALE) numerical scheme is employed based on the finite volume method [5]. According to code validation and grid dependence test, 1.3 million cells in an unstructured mesh with a grid resolution of 0.1cm is applied in the present work. Velocity-inlet and outflow boundary conditions are used along with no-slip, adiabatic walls.

3. Results and discussion

3.1 Non-reacting cases

Contour plots of the vorticity field with different inlet Reynolds numbers of $5.3 \times 10^4$, $6.3 \times 10^4$ and $7.4 \times 10^4$ are shown in Fig. 4. A reverse pressure gradient is usually induced along the axial direction due to swirl flow and gives rise to the appearance of CTRZs. High Reynolds numbers contribute to a larger recirculation zone and more frequent bubble- and helix-type vortex breakdown, which can be seen from the axial and tangential vorticity field distributions shown in Fig. 4. The stagnation point of vortex breakdown is shown to shift upstream with increasing Reynolds number. As the frequency of vortex core precession increases with increased Reynolds number [1], the large vortex structures are propelled outward from the centreline, and many vortices with high vorticity next to the combustor walls are observed with high Reynolds number, leading to increased tangential velocity due to the squeezing effects against the wall. This can be inferred from Fig. 4c, where high vorticity magnitudes appear around the chamber wall compared to Fig. 4a and Fig. 4b.
Both streamwise and spanwise vortex rings can be clearly identified from Fig. 4, as the Kelvin-Helmholtz (K-H) instability in the axial and azimuthal shear layers has developed in the flow field due to axial and tangential velocities that derived from the swirl flow. However, as the Reynolds number increases, the vortex rings become rare, and more helical vortices with high vorticity emerge due to the further increased azimuthal momentum. For the same reason, the flow structures on the parallel and transverse planes become more asymmetric at larger Reynolds number.

3.2 Reacting cases

To analyse the flame regimes in a partially premixed combustion process, a modified flame index is applied, $MFI = \frac{\nabla Y_{\text{fuel}} \cdot \nabla Y_{\text{O}_2}}{\left| \nabla Y_{\text{fuel}} \cdot \nabla Y_{\text{O}_2} \right|}$, where $Y_{\text{fuel}}$ and $Y_{\text{O}_2}$ represent the fuel and oxidizer mass fractions, respectively. When $MFI > 0$, the combustion is occurring in a premixed regime; the diffusion regime is confirmed when $MFI < 0$. The flame index distributions with different swirl numbers are shown in Fig. 5, where the flame is characterized by an iso-surface with $T=1800K$. The entire flame structure is shown in the centre of the figure, while the diffusion and premixed flames are exhibited at left and right positions, respectively. Proportion of premixed combustion increases with higher swirl numbers relating to intense bubble vortex breakdown and entrainment effects in the recirculation zones. The premixed region is also shown to move upstream when the swirl number increases further, which can be explained by improved mixing between the fuel and oxidizer ahead of the combustion taking place in the upstream region. Increased shear layer instability with increased swirl number leads to intense interactions between the flame and vortices, which results in a more wrinkled flame front and a non-uniform distribution of temperature around the shear layers. This is shown in Fig. 6.

The contour plots of the time-averaged temperature with different equivalence ratios at $Re=6.3 \times 10^4$, $p=3$ bar and CH: $N_2=4:1$ are shown in Fig. 7. When the equivalence ratio approaches the lean flammability of 0.45 for methane combustion, the high temperature region and flame length dramatically decrease due to the chemical reaction of fuel and excess air, which is crucial for emission reductions of thermal NOx. However, lean combustion tends to motivate combustion instabilities, such as flame flashback or blow off. The fast Fourier transform (FFT) of the flame temperature trace at different equivalence ratios is shown in Fig. 8. The main frequency and amplitude of the shear layer instability decreases when the equivalence ratio reduces from 0.8 to 0.65; harmonic waves corresponding to vortex breakdown instability also develop. However, as the ratio approaches the lean flammability, the main frequency and amplitude of the shear layer instability increase suddenly, and the fluctuation of temperature increases from 33.45 K to 80.01 K. Many harmonic waves appear around the main frequency, indicating the complexity of the flame instability at lean ratio conditions.

In the present work, nitrogen gas is used to form three mixed gases (CH$_4$:N$_2=1:0$, 4:1, 2:1), which are then examined to analyse the effect of nitrogen dilution on combustion dynamics. Due to the effects of N$_2$ dilution, heat release is decreased compared to pure methane gas and consequently the central recirculation zone is reduced due to lower thermal expansion. The high molecular weight of N$_2$ will tend to weaken the swirl flow and azimuthal momentum, which results in a lower frequency of vortex breakdown and poor mixing between fuel and oxidizers. As a result, the premixed combustion regime is
decreased during the operating process, but lower thermal $\text{NO}_x$ emissions are obtained due to a lower flame temperature and smaller reaction zones. The proportion of the premixed combustion regime and thermal $\text{NO}_x$ emissions with different $\text{N}_2$ content is shown in Fig. 9.

4. Conclusion

An experimental lean partially premixed swirling combustor is studied using the large-eddy simulation (LES) method for both non-reacting and reacting cases under different operating conditions. In the non-reacting cases, the influence of Reynolds number on vortex structures and vortex breakdown shows that a high Reynolds number contributes to more frequent bubble- and helix-type vortex breakdown and the appearance of high vorticity near the combustor walls. Vortex rings become more rare with larger Reynolds numbers. In the reacting cases, the influence of swirl number, equivalence ratio and nitrogen dilution on combustion dynamics are examined. The proportion of the premixed flame regime is shown to increase with swirl number and with shear layer instability and vortex breakdown instability. As the equivalence ratio approaches the lean flammability, the main frequency and amplitude of the shear layer instability increased suddenly, and the fluctuation of temperature increases from 33.45 K to 80.01 K. Many harmonic waves are also shown to appear near the main frequency. Flame instability at a lean ratio is very complex. Due to the larger molecular weight of $\text{N}_2$, additional inert gas tends to restrain the swirl flow, which decreases the size of recirculation zones and the frequency of vortex breakdown. The proportion of the premixed flame regime and $\text{NO}_x$ emissions are also reduced with higher $\text{N}_2$ content.

References