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Precessing motion in stratified radial swirl flow

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Abstract Vortex/flame interaction is an important mechanism for unsteady combustion in a swirl combustion system. Technology of low emission stirred swirl (TeLESS), which is characterized with stratified swirl flow, has been developed in Beihang University to reduce NO_X emission. However, large-scale flow structure would be induced in strong swirl flow. Experiments and computational fluid dynamics (CFD) simulation were carried out to investigate the unsteady flow feature and its mechanism in TeLESS combustor. Hotwire was firstly applied to testing the unsteady flow feature and a distinct mode with 2244 Hz oscillation frequency occurred at the pilot swirl outlet. The flow mode amplitude decayed convectively. Large eddy simulation (LES) was then applied to predicting this flow mode and know about its mechanism. The deviation of mode prediction compared with hotwire test was 0.8%. The spiral isobaric structure in pilot flow passage indicates that precessing vortex core (PVC) existed. The velocity spectrum and phase lag analysis suggest that the periodic movement at the pilot outlet was dominated by precessing movement. Negative tangential momentum gradient reflects that the swirl flow was unstable. Another phenomenon was found out that the PVC movement was intermittently rotated along the symmetric axis.

1. Introduction

Green energy is the topic of 21st century. As for aero gas turbine combustor, lean combustion technologies are developed, such as lean premixed prevaporized (LPP), lean direct injection (LDI) and rich burn-quench-lean burn (RQL), to reduce NO_X emission.[1,2] However, lean combustion system is susceptible to the combustion instability, which is a resonant phenomenon coupled between unsteady heat release and acoustic mode of combustor. This instability occurs with large amplitude of periodic pressure or velocity oscillation in combustor, leads to the failure of high-temperature component and finally threatens the engine's safety.[3,4]

Technology of low emission stirred swirl (TeLESS) for civil aero-engine combustor was developed in Beihang University to reduce NO_X emission. Concentric staged partial premixed combustion is applied to this technology, in which the multi-hole-air-injection is adopted in main stage to generate the premixed flame and single fuel spray is adopted to realize the diffusion combustion to stabilize main stage flame.[5] In terms

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of partial premixed swirling combustion, two mechanisms dominate the unsteady combustion, the first one is equivalence ratio oscillation, the second one is vortex/flame interaction.[6] Equivalence ratio oscillation time lag phenomenon was observed and proposed by Lieuwen et al.,[7] Lee et al.[8] and Nguyen[9] measured the equivalence ratio oscillation through infrared absorption using 3.39 μm HeNe laser system. Large eddy simulation was applied by Huang and Yang[10] to investigate the interaction between large-scale flow structure and flame in a model swirl combustor. Large eddy simulation was also applied by Sengissen et al.[11] in a stratified swirl combustion system and the interaction between pilot stage spray flame and precessing vortex was confirmed as the nonlinear mechanism. Bellow et al.[12] studied the nonlinear flame transfer function in a swirl stabilized model combustor. The rolling up and shedding movements of flame were the saturation mechanism. Several phenomena were observed in Balachandran et al's study.[13] In turbulent swirl premixed combustion system, small disturbance with higher exciting frequency would be easier to cause the rolling up of flame in shear layer, and the critical disturbance would get larger with increasing equivalence ratio.

As for swirl flow, symmetry ring vortex and asymmetry spiral vortex would be observed in common under large swirl number.[14,15] The unsteady flow mode can be described by Strouhal number (St), and this dimensionless number is almost independent of flow Reynolds number.[14] In aeroengine combustor, the swirl number is generally designed around 0.6 to generate a stale centroid recirculation to stabilize the flame.[16] Under this circumstance, ring vortex or spiral vortex would occur. Questions are raised as to whether the large-scale flow structure would occur in TeLESS combustor and where they would be produced and developed. In order to answer those questions, unsteady flow feature is firstly diagnosed using hotwire measurement and the corresponding mechanism is then studied by large eddy simulation. Syred[14] has described that 1. Processing vortex core(PVC) mode frequency(f_0) is quasi-linear with the bulk flow velocity; 2. The intensity of PVC movement relies on the fuel/air mixing properties in partial premixed combustion; 3. The PVC mode frequency changes from f_0 to $(0.8–1)f_0$ with non-reacting flow condition transited to partially premixed reacting flow condition. Consequently, the present investigation was carried out under non-reacting flow condition (without combustion), because it is conductive to cost reduction and urgent technology transition on single nozzle test research period.

2. Experiment

Instantaneous flow velocity at the adjacent downstream of TeLESS swirler was measured by 1D-hotwire. As the unsteady flow mode was most concerned in this study, less attention was paid to three-dimensional character of swirl flow and the datas obtained from 1D-hotwire is enough. The test system is illustrated in Fig. 1. The flow rate was controlled by upstream valve and displayed by differential pressure sensor indirectly because the bulk flow velocity U is proportional to the square of pressure drop ΔP when flow Mach number is smaller than 0.2. The hotwire probe was arranged at downstream of swirler and was installed onto the displacement component, which has a displacement resolution of 2.5 μm. Transparent organic glass tube was applied to adjusting the hotwire probe. The hotwire probe arrangement is illustrated in Fig. 2; the hotwire was parallel to the radial direction of swirler. The tangential velocity w, satisfying the right-hand rule, is defined as positive. The plane $x0y$ is perpendicular to the ground.

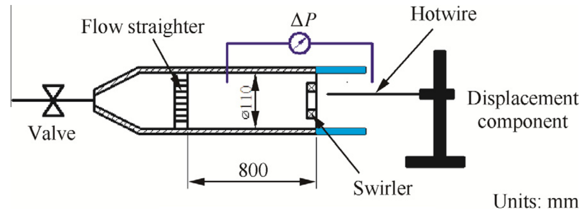
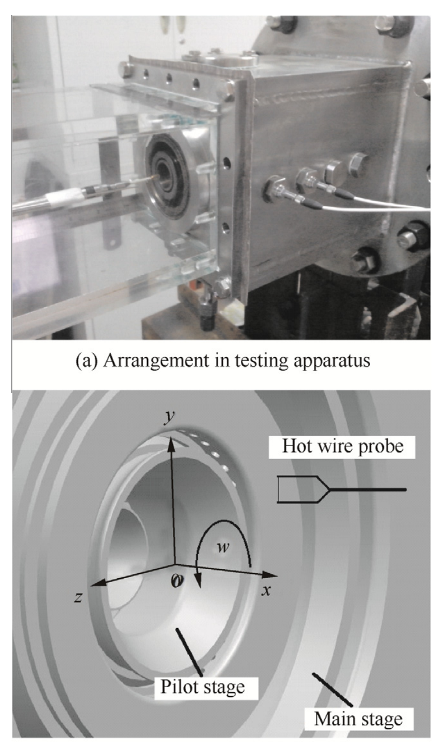


Fig. 1 Hotwire test system.

Scheme of TeLESS swirler is illustrated in Fig. 3, where three swirlers are concentric and the flow is referred to as stratified flow. The main stage inlet is perforated. And the pilot is combined by two counter radial swirlers. The swirl number of 1st and 2nd swirler at pilot stage is 0.67 and −0.72 respectively, and the swirl number at main stage is −0.6. The negative sign means the counter rotating direction. The variable R_P is the radius of the pilot outlet. The pressure drop cross swirler (ΔP) during the test was to ensure that the bulk velocity under atmosphere condition was equal to takeoff design condition in real engine combustor. $\Delta P = 3.92$ kPa was applied and the corresponding flow Reynolds number of pilot stage outlet and main stage outlet was 1.16×10^5 and 2.97×10^5 respectively.[17] The hydraulic diameter of each stage outlet was applied in estimating the Reynolds number. In order to know the spatial feature of this stratified swirl flow, the flow velocity at different position was scanned. The scanning was carried out in the $x0y$ plane (see Fig. 2) and the scanning grids are illustrated in Fig. 3 as well. The grid



(a) Arrangement in testing apparatus

(b) Position at downstream of swirler

Fig. 2 Hotwire arrangement.