Chinese Journal of Aeronautics, (2018), **xxx**(xx): xxx–xxx

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

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Large-eddy simulation and linear acoustic modeling of entropy mode oscillations in a model combustor with coolant injection

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Received 21 July 2016; revised 27 May 2017; accepted 31 January 2018

KEYWORDS

Acoustic wave;
Combustion instability;
Coolant injection;
Entropy;
LES;
Network method;
Rumble;
Self-excited

Abstract Lean-burn combustor is particularly susceptible to combustion instability and the unsteady heat release is usually considered as the excitation of the self-maintained thermo-acoustic oscillations. The transverse coolant injection is widely used to reduce the temperature of burnt gas, but on the other hand, it will introduce temperature fluctuation inside the combustor. Therefore, it is necessary to consider the influence of the coolant injection on combustion instability, and evaluate its dynamic feature. In this paper, Large-Eddy Simulation (LES) of the self-excited pressure oscillations in a model combustor with coolant injection is carried out. The analysis of transient flow characteristics and the identification of the pressure modes confirm that one of the low frequency pressure oscillations is related to entropy fluctuations, which is known as rumble combustion instability. The LES results show that transient coolant injection is another excitation of temperature fluctuation other than unsteady combustion. The amplitude of the entropy mode oscillation increases with increasing coolant air mass whereas the change of its frequency is insignificant. According to the major feature of entropy wave oscillation caused by coolant injection, a compact coolant injection model is proposed and applied in the One Dimensional (1D) Acoustic Network Method (ANM). Key correlations used in the model match well with LES data in low frequency range. This means that the coolant injection model is a complex one reflecting the interaction of the fluctuating coolant mass, pressure and temperature. Finally, the combustion instability frequencies and modes predicted by acoustic network method are also in good agreement with LES results.

1. Introduction

Lean combustion technology can significantly reduce the burnt gas temperature and the thermal NO_x emissions. Therefore, it has been widely used in industrial applications, such as aero-engine combustors and ground-based gas turbine combus-

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Peer review under responsibility of Editorial Committee of CJA.

Production and hosting by Elsevier

https://doi.org/10.1016/j.cja.2018.05.013

Please cite this article in press as: ZHANG M, LIANG A Large-eddy simulation and linear acoustic modeling of entropy mode oscillations in a model combustor with coolant injection, *Chin J Aeronaut* (2018), https://doi.org/10.1016/j.cja.2018.05.013

tors.[1,2] However, lean combustion is prone to combustion instability problems, which is susceptible to synchronized pressure oscillations and can heavily damage combustion facilities.

According to the work of Lieuwen and Yang,[3] the basic principle of combustion instability is that the standing acoustic waves in the chamber are in phase with the unsteady heat release. However, there are different variances in the mechanism of thermo-acoustic instability for different frequency ranges. For instance, Dowling and Stow,[4] Zhu et al.,[5,6] and Eckstein and Sattelmayer[7,8] studied one kind of pressure oscillation mode in combustion chamber under low-power working conditions. The amplitude of the pressure oscillations of this mode is slightly weaker than that of the standing wave mode, but the corresponding time of the oscillation is in the same scale of flow transport time. For this kind of oscillation mode, entropy fluctuations are generated by the unsteady heat release and transport with flow. At the converging boundary of the choked nozzle, they are converted into pressure wave and propagate in opposite direction compared to the flow direction. The upstream propagating pressure wave leads to velocity fluctuation of the inlet air and fuel and aggravates the change of heat release rate. If this feedback loop is established, the self-excited rumble combustion instability can be maintained.

Previous studies mainly indicated that entropy waves are generated by the unsteady combustion heat release. Recently, Motheau et al.[9] used Large-Eddy Simulation (LES) to study the combustion instability in a real configured aero-engine combustor. In their work, combustion instability of entropy mode was simulated and the coolant air injection was claimed to excite the entropy wave. Therefore, the pressure oscillation of entropy mode is more obvious compared to the former reports. Ichihashi et al.[10,11] investigated the combustion instability in a real industrial single swirler combustor. Among their results, the measurement of transient heat release shows that the coolant injection is involved in the combustion oscillation loop, and enhances the self-excited pressure oscillations.

In the previous works, coolant injection directly or indirectly contributes to unstable combustion. However, as demonstrated by Motheau et al.,[9] the coolant injection is an important excitation of the entropy fluctuation in the dilution zone.

In steady flow, the coolant jet is utilized to dilute burnt gas and reduce the temperature at the inlet of the high-pressure turbine. Lefebvre and Ballal,[12] and Lieuwen and Yang[13,14] summarized the empirical correlation which is deduced from Bernoulli equation and widely used in industry, written as

$$m_{\mathrm{c}} = C_d A_{\mathrm{c}} [2\rho_{\mathrm{c}}(p_{\mathrm{an}} - p_{\mathrm{ch}})]^{0.5} \tag{1}$$

where m_{c}, A_{c} and ρ_{c} are the mass flow rate, area and density of the coolant air, respectively, C_d is the effective coefficient, and p_{an} and p_{ch} stand for the static pressure in combustor annuls and the chamber, respectively. In general, about 65% of the total air mass is utilized for burning in a lean-burn combustor, 25% of the air is designed for the liners cooling, and roughly 10% (or less) of air is assigned for dilution.[15] Although the development trend is to reduce the mass of the dilution air in the ultra-lean burn combustor in order to offer sufficient air for lean-burn and cool down the combustor wall,[16] dilution injection is still a conservative and effective approach to adjust the specific radial thermo-loading distribution in high-pressure turbines.

In transient flow, on the other hand, dilution jet is pulsed and influenced by the chamber pressure fluctuations.[17] Thus the diluted gas temperature in combustor also varies and the entropy wave is introduced. However, this effect on combustion instability is not directly and fully considered in the previous prediction methods. Until now, most interests are mainly focused on the averaged temperature and sound speed before and after the dilution hole. For example, the thermo-acoustic network model developed by Hsiao et al.[18] and Eckstein and Sattelmayer[7,8] is representation for this category.

In order to improve the prediction capability of the combustion instability caused by entropy wave, Motheau et al.[9] proposed an acoustic boundary condition for solving the Helmholtz equation. This approach correlates density and acoustic velocity fluctuation in the flame region. Furthermore, the forwarded acoustic wave, which is reflection of the entropy wave choked exit, is modified via additional boundary conditions in order to enclose transport source term in Helmholtz equation. With this approach, the calculated frequencies of entropy combustion instability contain the interaction between entropy oscillation and acoustic wave. However, this method needs the density correlation as the input parameter which must be obtained from other LES calculations.

In this context, the work aims to study entropy mode oscillations with coolant injection and develop a fast and reliable prediction method for industry application. Thus, LES and One Dimensional (1D) Acoustic Network Method (ANM) are carried out. Firstly, LES is used to study self-excited oscillation in a model single swirler combustor. The frequency, mode characteristics and the transient physical process of the entropy mode oscillation are analyzed in detail. Subsequently, an analytical model is proposed to correlate the coolant injection with temperature and pressure fluctuations. Based on this model, a thermo-acoustic network including the influence of the transverse jet is established and validated by LES results. Furthermore, the predicted combustion instability frequency and pressure modes are both compared with the LES.

In the following part, this paper consists of four sections: LES method and the studied combustor are introduced first, the analysis of the LES results is presented next, the derivation of the coolant injection model is addressed in the third part, and the conclusion is drawn finally.

2. Computational setup

2.1. Brief description of LES method

The turbulent reacting flow is governed by the Navier-Stokes equations and the multi-species transport equation coupled with reaction sources, which are filtered through the spatial cells:

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial}{\partial x_j}(\bar{\rho}\tilde{u}_j) = 0 \tag{2}$$

$$\frac{\partial}{\partial t}(\bar{\rho}\tilde{u}_i) + \frac{\partial}{\partial x_j}(\bar{\rho}\tilde{u}_i\tilde{u}_j) = \frac{\partial}{\partial x_j}(-\delta_{ij}\bar{P} + \tilde{\tau}_{ij} - \tau^{\mathrm{SGS}}) \tag{3}$$

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