Numerical simulation of unstable combustion behavior in a gas turbine combustor

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1. Introduction

Reduction of combustion pollutants like NOx in modern combustor systems is strongly required and lean premixed combustion is one promising way to achieve it. Lean premixed combustion, however, is prone to combustion instabilities and this can sometimes cause detrimental damage to combustor systems. Research on combustion control is a key issue in achieving stable combustion over a wide range of operation conditions in lean premixed combustion. Our final goal is to realize stable combustion in gas turbine combustors.

Understanding combustion dynamics in gas turbine combustors is thus necessary toward the final goal of combustion control. Recent progress in numerical simulation techniques has enabled to us to use computational fluid dynamics simulation as a useful tool in combustion research [1]. Here, we simulate unstable combustion in a lean premixed gas turbine combustor to understand the dynamics and mechanisms. Large Eddy Simulation (LES) techniques are utilized to capture unsteady phenomena in the combustor, and the combustion model is based on the flamelet assumption [2]. Time-series datasets are obtained and analyzed in terms of flowfield structures, oscillation frequencies, flame/vortex interaction and coupled effects with heat release. And flow conditions such as the inlet gas temperature and the global equivalence ratio are changed to see the difference in flame behavior.

2. Combustor and analysis method

The combustor considered here is a swirl-stabilized gas turbine combustor. The combustor length is 0.3m and the swirl number is set at about 0.8. Methane/air premixed gas of equivalence ratio of 0.55-0.7 is supplied into the combustor at about 30m/s. The pressure is set at 1 atm and the unburned gas temperature is varied from 400K to 700K.

The three-dimensional Navier-Stokes equations are the governing equations for the system. Compressibility must be included to capture pressure wave propagation inside the combustor. Combustion is modeled using the G-equation (flamelet) model [2,3]. The LES subgrid model is based on the dynamic model. Discretization is based on Roe's upwind formulation [4] and time integration is done using the two-stage Runge-Kutta method. Inflow and outflow boundary conditions are carefully treated because they influence acoustic characteristics of the combustor. Here, non-reflecting boundary conditions with a correction term to sustain the total mass flow rate proposed by Poinsot et al. [5] are imposed.

3. Results and discussion

Figure 1 shows the time averaged flame shape and velocity field for a case of inlet temperature of 700K and equivalence ratio of 0.55. A recirculation zone is created along the centerline and this region serves for flame holding because the hot burned gas is pushed upstream. Recirculation zones are also formed in the corner regions due to sudden expansion.

The temporal pressure trace reveals that there are some resonance modes in the combustor. Figure 2 shows the Fourier transform of the pressure trace. The basic mode is found around 740 Hz, and this frequency corresponds to the longitudinal quarter-wave mode determined by the combustor length and the burned gas sonic speed.

Time-series analysis of flame/vortex interaction is shown in figure 3. Because the combustor is in acoustic resonance, pressure waves are propagating inside it. This causes velocity fluctuations in the inlet section leading to periodic vortex shedding from the dump plane. These vortices change flame shape and location at every moment. Because heat release occurs at the flame front, this vortex/flame interaction changes the location and total amount of heat release. If the pressure and heat release fluctuations satisfy the Rayleigh criterion, the combustor system is unstable. Figure 4 shows the local Rayleigh index distribution around the dump plane. Most part shows positive Rayleigh index and the global Rayleigh index, obtained by integrating the distribution over space, is 2.948 (non-dimensional) and positive. Thus, in this case, the unstable combustion behavior is driven by the coupling between fluctuations in pressure, velocity and heat release. Combustion control will focus on how to change these links.

If the inlet temperature is lowered to 400K, the mean pressure fluctuation amplitude becomes about 1.2 times larger. And if the equivalence ratio is increased to about 0.6, the amplitude also becomes larger. Figure 5 shows some part of the pressure traces of the three cases. These trends are the same as what is mostly observed in experiments [6]. Total amount of heat release, thermal expansion ratio and turbulent burning speed are the factors affecting the behavior. The oscillation amplitude is also dependent on other parameters, so further investigation will be necessary.

4. Summary

LES-based combustion simulations have been conducted in a swirl-stabilized lean premixed gas turbine combustor. In the combustor, acoustic resonance is observed and the flame changes its shape and location three-dimensionally. The unstable combustion behavior is driven by the coupling between pressure, velocity and heat release fluctuations. The oscillation amplitude changes as some flow conditions are varied. The amplitude is dependent on many factors and further investigation will be needed.

5. References

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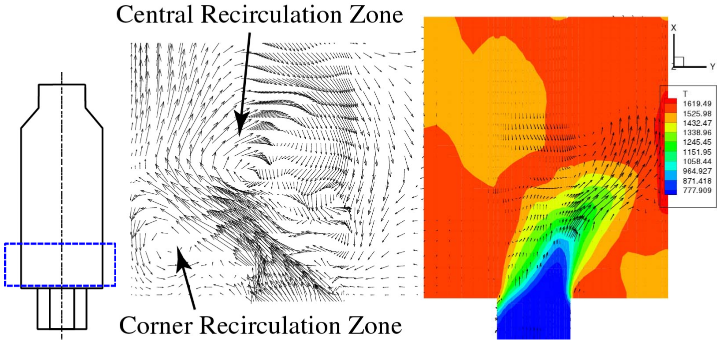

Figure 1 Time averaged velocity and temperature field near the dump plane

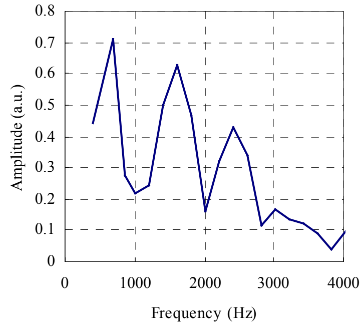

Figure 2 FFT of combustor pressure trace

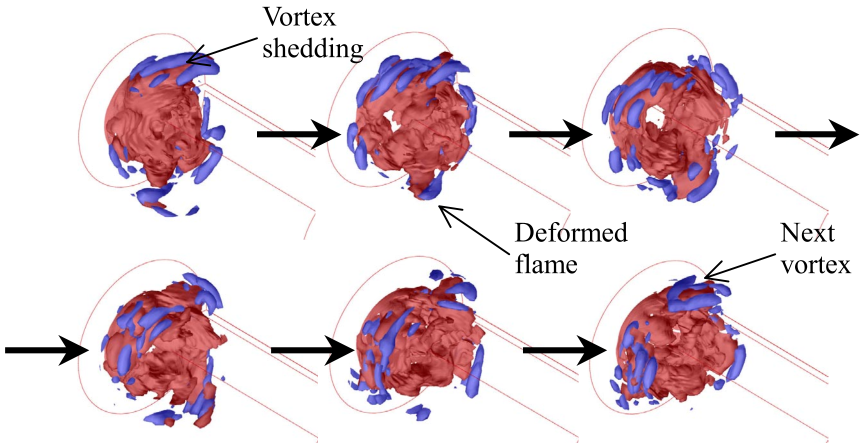

Figure 3 Vortex/flame interaction: time interval between each image is about 0.28ms.
(blue: vortical structures, red: flame surfaces)

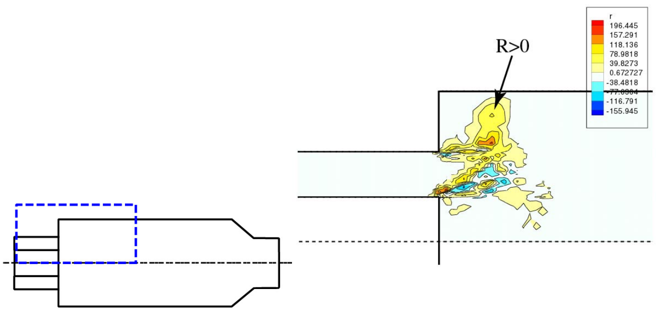

Figure 4 Local Rayleigh index distribution

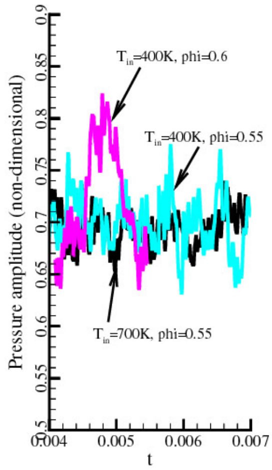

Figure 5 Comparison of pressure traces