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LES of combustion instabilities in a lean premixed gas turbine combustor

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ABSTRACT

This paper presents a numerical study on combustion instabilities in a lean premixed gas turbine combustor. In lean premixed combustion, flame behavior may sometimes become unstable and controlling unstable combustion is an important issue. We have conducted numerical investigations using large eddy simulation (LES) techniques to understand flame dynamics in a swirl-stabilized gas turbine combustor.

Inside the combustor, acoustic resonance modes are observed and the strongest mode is the longitudinal quarter-wave mode. The pressure fluctuations can change the velocity field every moment and this changes the flame location and shape. Thus, heat release rate is also affected by the flow fluctuations. These effects are interconnected to sustain the unstable motions. The oscillation behavior changes depending on the flow conditions and achieving combustion control lies in how to change the flow field in a proper manner.

INTRODUCTION

Regulations for low-emission gas turbine combustors are getting more and more stringent due to environmental concerns. Especially, reducing NOx emissions is one of the most important issues in modern combustion systems. Lean premixed combustion is one promising way to reduce NOx emissions because the flame temperature is comparatively low, but it is prone to combustion instabilities that may lead to mechanical damage or blow-off. Achieving combustion control to widen the stable operation range is our final goal and a detailed understanding of flame dynamics is needed to realize it.

Experimental investigations have been conducted worldwide for this goal. Several experimental techniques have been applied and velocity field, chemiluminescence, pressure field and other properties have been measured (Taupin, 2002). Experimental measurements, however, are basically one-dimensional or two-dimensional, and in some cases it is even difficult to conduct measurements.

Recent progress in numerical simulation techniques has enabled us to conduct practical-scale combustor simulations. Fully resolved DNS, however, is of course impossible in such a scale. LES deals with spatially filtered flow equations and can give unsteady solutions in practical-scale devices. One of the advantages of numerical simulations is that they can give three-dimensional results. Thus it is expected that numerical simulations will help us understand the flow field more thoroughly.

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LES, however, requires modeling of small-scale phenomena that cannot be resolved in rather coarse LES grid systems. Combustion is usually determined by small-scale phenomena such as diffusion and chemical reactions and these are subgrid-scale phenomena. Thus, combustion modeling is a key issue in LES and several models have been proposed so far (Poinsot, 2001).

Menon and coworkers (Stone, 2002) have demonstrated the effectiveness of LES in reproducing unstable combustion dynamics in real-scale combustors. Their methods are mostly based on the flamelet combustion model. They have analyzed acoustic resonance in the combustor and the effects of flow conditions such as swirl number and equivalence ratio. Their results are in good agreement with experimental observations and the flamelet model has been proved to be a good approximation unless the turbulent intensity is extremely high.

Poinsot and coworkers (Colin, 2000) have utilized a slightly different approach called thickened flame method. In this model, a flame is artificially thickened so that it can be resolved on an LES grid system. Diffusion coefficients and chemical reaction rates are artificially changed to keep the laminar flame speed at the same value. Although the Damköhler number is changed by thickening, their results are in good agreement with experimental data. One of the advantages of this approach is that this formulation can include the effects of chemical reactions.

In the present study, we conduct numerical simulations in a lean premixed gas turbine combustor to understand unstable flame behavior for combustion control in the future. The turbulent intensity is not extremely high, thus the flamelet assumption can be applied to the present configuration. Acoustic characteristics, flow field properties and mechanisms of unstable flame behavior are investigated by LES.

NUMERICAL IMPLEMENTATION

The combustor simulated here is a swirl-stabilized gas turbine combustor as shown in Figure 1. The combustor length is L=0.3m and diameter D=0.5L. An inlet tube is connected to the combustor and swirl is given in this section. Swirl vanes are not directly solved, but a hypothetical body force is added to the flow in the inlet section to generate swirl. The exit is contracted to accelerate the burned gas. The fuel is methane and the unburned gas is assumed to be perfectly mixed. The unburned gas temperature is set at 400K-700K, pressure at 1atm, velocity at 30m/s and equivalence ratio at 0.55-0.6.

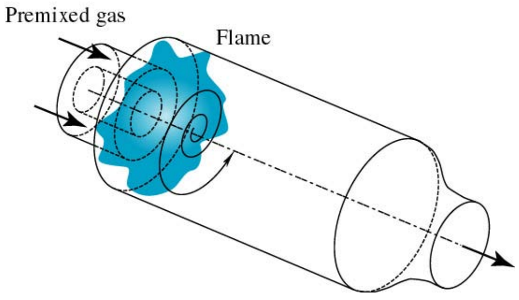

Fig. 1 Combustor configuration

The governing equations of the system are the three-dimensional Navier-Stokes equations. Pressure wave propagation in the combustor plays an important role in determining flame behavior, so compressibility must be included.

$$\begin{aligned}&\frac{\partial \rho}{\partial t}+\frac{\partial \rho u_j}{\partial x_j}=0\\&\frac{\partial \rho u_i}{\partial t}+\frac{\partial\left(\rho u_i u_j+\delta_{ij} p\right)}{\partial x_j}=\frac{\partial \tau_{ij}}{\partial x_j}\\&\frac{\partial E}{\partial t}+\frac{\partial(E+p) u_j}{\partial x_j}=\frac{\partial\left(\tau_{ij} u_i+q_j\right)}{\partial x_j}\end{aligned} \tag{1}$$

In premixed combustion, the flame thickness is usually very small and it is usually impossible to resolve the inner structures of flame on an LES grid. So the flame propagation should be modeled. Here, we use the flamelet model described by the so-called G-equation. This model is simple but gives good results. The flame front is treated as a discontinuity surface between unburned (G=0) and burned (G=1) gases. This model implicitly assumes that the chemical reactions are always occurring at the flame front and cannot include extinction or re-ignition. This can be justified if the equivalence ratio is higher than the lean flammability limit. The G-equation is given by

$$\frac{\partial \rho G}{\partial t}+\frac{\partial \rho G u_j}{\partial x_j}=\rho s_L|\nabla G| \tag{2}$$

where s_L is the laminar burning velocity. This equation means that the flame front is convected by the flow and propagates normal into the unburned gas with the speed of s_L. The laminar burning velocity cannot be directly obtained in the present method, so it is given from experimental measurements or CHEMKIN calculations. The effect of flame strain and curvature on laminar burning velocity is included (Peters, 2000) but, as described below, small scale wrinkling cannot be fully resolved in LES and the effect is finally included in turbulent burning velocity modeling.

LES spatial filtering is applied to the above equations. The filtered momentum equation, for example, is

$$\frac{\partial \bar{\rho} \tilde{u}_i}{\partial t}+\frac{\partial \bar{\rho} \tilde{u}_i \tilde{u}_j}{\partial x_j}=-\frac{\partial \bar{p} \delta_{ij}}{\partial x_j}+\frac{\partial \bar{\tau}_{ij}}{\partial x_j}-\frac{\partial \tau_{ij}^{sgs}}{\partial x_j} \tag{3}$$

where the bar denotes averaging and the tilde Favre averaging. The last term is an unresolved subgrid term and modeled using the dynamic procedure as

$$\tau_{ij}^{sgs}=\bar{\rho}\left(\widetilde{u_i u_j}-\tilde{u}_i \tilde{u}_j\right)=-2 \bar{\rho}\left(C_s \Delta\right)^2\left|\bar{S}_{ij}\right| \bar{S}_{ij} \tag{4}$$

where C_s is a coefficient determined dynamically from local flow conditions, Δ filter scale and $\bar{S}_{ij}$ resolved strain rate tensor.

The G-equation is also filtered and yields

$$\frac{\partial \bar{\rho} \tilde{G}}{\partial t}+\frac{\partial \bar{\rho} \tilde{G} \tilde{u}_j}{\partial x_j}=-\frac{\partial}{\partial x_j}\left[\bar{\rho}\left(\widetilde{u_j G}-\tilde{u}_j \tilde{G}\right)\right]+\widetilde{\rho s_L|\nabla G|} \tag{5}$$

The flame propagation term of the G-equation is modeled as

$$\widetilde{\rho s_L|\nabla G|}=\bar{\rho} \tilde{s}_T|\nabla \tilde{G}| \tag{6}$$

where $\tilde{s}_T$ is called the turbulent burning velocity. It represents the effect of flame surface increase due to turbulent flame wrinkling. Here, it is given by an empirical relation of

$$\frac{\tilde{s}_T}{s_L}=1+C\left(\frac{u'}{s_L}\right)^n \tag{7}$$

where u' is the subgrid turbulent intensity and model constants are set at $n=1.0$ and $C=1.5$. Details are given, for example, in Peters (2000) or Poinsot (2001).

Numerical methods are based on finite-volume discretization. The convective terms are constructed by modified Roe's upwind numerical flux formulation (Wada, 1989). Time integration is done by two-stage Runge-Kutta method. Combustion chamber walls are treated as non-slip adiabatic walls. Incoming and outgoing boundary conditions are given based on Poinsot's method (Poinsot, 1992). The concept is fundamentally to give non-reflecting conditions. But perfectly non-reflecting conditions are not appropriate because the pressure difference between the inlet and exit will vanish and the mean mass flow rate cannot be kept. This can be avoided if correction terms are added to the boundary characteristic equations. The correction terms are, for example for velocity, in the form of

$$C=\sigma\left(u-u_t\right) \tag{8}$$

where u_t is the target velocity and σ is a parameter determined from local flow conditions. Details are shown in (Poinsot, 1992).

The number of grid points is about 1 million. The grid system for analysis is somewhat coarse to make the integration time shorter. Calculations using finer grid systems are also underway.

RESULTS AND DISCUSSION

First, calculations conditions are set at the inlet temperature of 700K, velocity of 30m/s, pressure of 1atm and equivalence ratio of 0.55.

Figure 2 shows the averaged velocity field near the dump plane. A recirculation zone is formed along the centerline due to swirling motion of the incoming flow. This recirculation carries the hot burned gas upstream and the flame is stabilized in this region. Recirculation zones are also created in the corner regions due to sudden expansion. This is a typical flow pattern observed in swirl-stabilized gas turbine combustors (Taupin, 1998).

Figure 3 shows the averaged flame shape. The flame is formed behind the dump plane and the balance between the flow velocity and the turbulent burning velocity determines the flame shape.

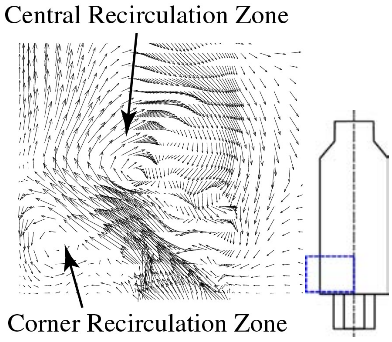

Fig. 2 Averaged velocity field near the dump plane
Visualized region is indicated by dashed lines.

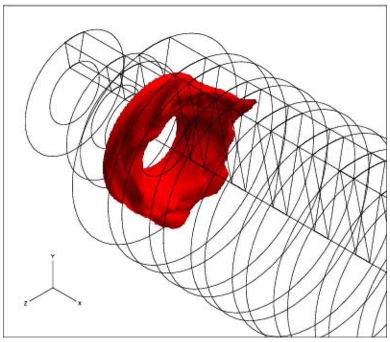

Fig. 3 Averaged flame shape

Instantaneous flow field is much more complicated and it is changing every moment.

First, the pressure field is analyzed. Figure 4 shows the time history and FFT result of combustion chamber pressure measured at a point near the dump plane. The real calculation time is much longer than the period shown in Figure 4.

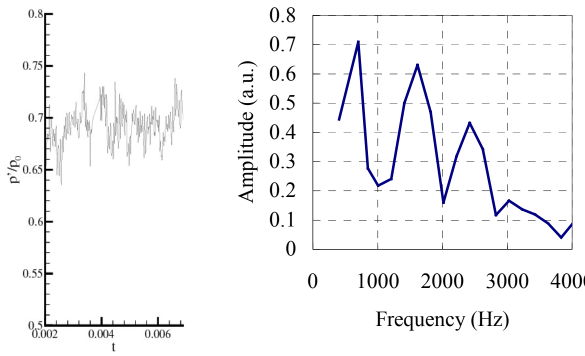

Fig. 4 Pressure history in the combustor and FFT result

There are several modes and the FFT result reveals that the strongest mode is about 740Hz. The acoustic wavelength of this mode can be analyzed by time-averaging the combustor wall pressure. Figure 5 shows the distribution of time-averaged pressure fluctuation amplitude. The amplitude is the largest at the combustor inlet and the smallest at the exit. Higher modes are also observed but not as strong as the basic one. This result shows that the basic acoustic mode is quarter-wave resonance.

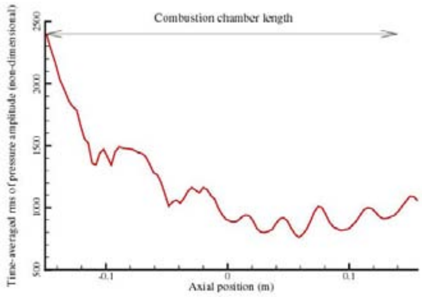

Fig. 5 Spatial distribution of time-averaged pressure fluctuation amplitude

The frequency of the quarter-wave mode can be readily estimated by the combustor length and the burned gas speed of sound. In the present case, it is

$$f = \frac{a}{4L} \approx 700Hz \tag{9}$$

and this value is close to the frequency of the present calculation. Experimental results usually show the same trend of excitation in this kind of combustor and the present method succeeds in capturing the acoustic resonance in the combustor.

The acoustic resonance in the combustor changes the velocity field. This will lead to periodic vortex shedding near the dump plane. Figure 6 shows a time sequence of flame shape identified by the G value of 0.5 and vortical structures identified by vorticity magnitude. These 6 images correspond to nearly one acoustic period. Several vortical structures are observed and these are generated and convected periodically. The shedding frequency seems synchronized with the acoustic frequency. Figure 7 shows the history of vorticity magnitude at point A, which is indicated in Figure 6 by a dot. Peaks of vorticity magnitude are seen in accordance with the acoustic frequency.

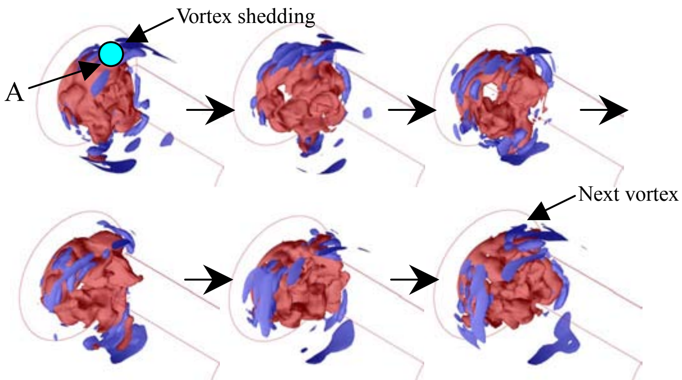

Fig. 6 Time sequence of flame shape (red) and vortical structures (blue)

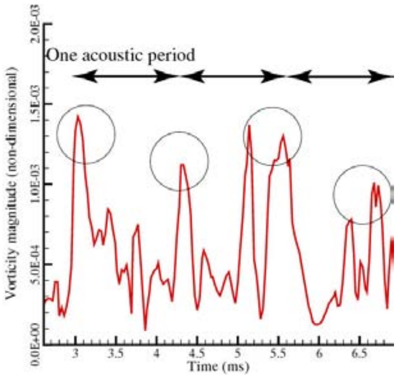

Fig. 7 History of vorticity magnitude at point A in Figure 6

The flame shape is locally affected by the flow filed. Thus, these vortical structures change the flame shape and location. One example is shown in Figure 8. This figure shows a time sequence of the flame front shape and the velocity vector field on a plane around the dump plane. The unburned flow comes from left and the solid red line denotes the flame front. It should be noted that the flow is three-dimensional and swirling.

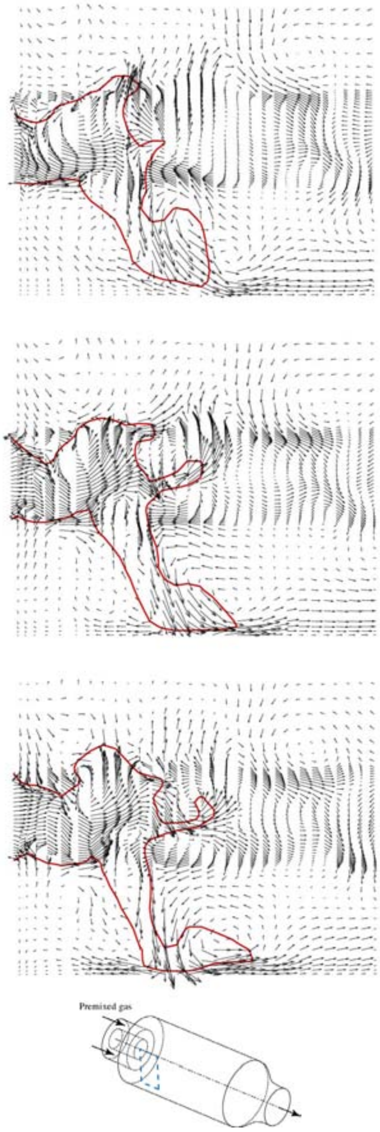

Fig. 8 Instantaneous velocity field and flame front shape
Visualized region is indicated by dashed lines.

There are several rotating eddy structures and the flame front is distorted by their motions. Also, because the effect of flame stretch and curvature affects the burning rate, the turbulent flame velocity is changed by flame motions.

Fluctuations in flame shape and location cause heat release fluctuations. If pressure and heat release fluctuations are in phase, the acoustic energy is fed from combustion energy and the system is unstable. This is called Rayleigh's criterion, and widely used to evaluate the stability of combustor systems. The global Rayleigh index is given by

$$R = \frac{1}{V}\frac{1}{T}\int_{V,T} p'(\mathbf{x},t)\dot{q}'(\mathbf{x},t)\,dtdV \tag{10}$$

where p' is pressure fluctuation and $\dot{q}'$ heat release fluctuation. Integration is done over the space and time. If the global Rayleigh index is positive, the system is unstable because some part of combustion energy is fed into acoustic energy, and if negative, it is stable. The local heat release rate is estimated by the definition of G-equation as

$$\dot{q} \propto \rho_u s_T \Delta h A_f / V \tag{11}$$

where ρ_u is the unburned density, Δh heat generated by combustion, A_f local flame surface area and V volume of a cell considered. Figure 9 shows the local Rayleigh index distribution for this case, which is obtained by integrating fluctuations over time. As the figure indicates, most of the region is positive and some part negative. The global Rayleigh index given by Eq. (10) is in this case 2.498 (non-dimensional), so the combustor system is globally unstable.

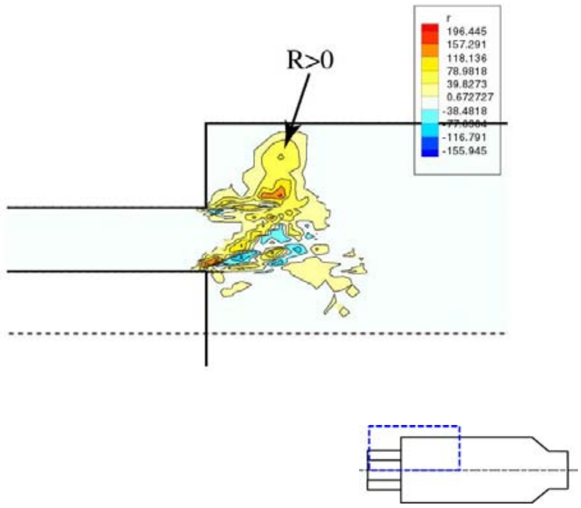

Fig. 9 Local Rayleigh index distribution
Visualized region is indicated by dashed lines.

From these results, it can be said that three major factors are driving the unstable flame behavior: acoustic resonance, velocity fluctuations and heat release fluctuations. Due to acoustic resonance, pressure waves are propagating inside the combustor. The strongest mode is the quarter-wave mode and some higher modes are also present. Pressure fluctuations induce velocity fluctuations and lead to periodic vortex shedding at the dump plane. These vortices can affect the flame shape and location, inducing heat release fluctuations. And some energy is fed into the acoustic energy again. This cycle is repeated to sustain the unstable combustion behavior. Combustion control may lie in how to change these links.

The present analysis does not include equivalence ratio fluctuations that mainly occur in fuel/air supply flows. If this effect is in phase with other factors, it is expected to amplify the oscillation. Future investigations will include this effect.

The numerical grid system used in the present calculations is rather coarse but fine enough to resolve the global mechanisms of combustion instabilities such as vortex shedding. But the turbulent burning velocity modeling is closely related to flame wrinkling and subgrid turbulent intensity. Results using finer grid systems will be compared in the future to investigate the effect of flame modeling.

Effect of Flow Conditions

The pressure oscillation amplitude is sensitive to flow conditions. Phase difference between pressure and heat release, thermal expansion rate or heat release rate, and other factors are affecting the flame dynamics.

Detailed trends and mechanisms are still not clear and future investigations are necessary, but we have conducted some preliminary calculations to see how the trend would be. First the unburned gas temperature is lowered to 400K to see the effect of preheating. Then the equivalence ratio is increased to 0.6 to see the effect of total heat release. Figure 10 shows the three cases. The black line indicates the first case and the cyan line is the case of less preheating. The amplitude becomes slightly larger. The red line is the case of less preheating and the equivalence ratio of 0.6. Then the amplitude becomes larger.

The thermal expansion ratio and heat release rate are partly playing a role in determining the amplitude. With preheating, the thermal expansion ratio becomes smaller and velocity acceleration due to thermal expansion is also smaller. Some experimental results show the same trend (Lefebvre, 1998), but it is also pointed out that the chemical time difference may also be one cause of this. We need more investigation in the future to examine detailed mechanisms.

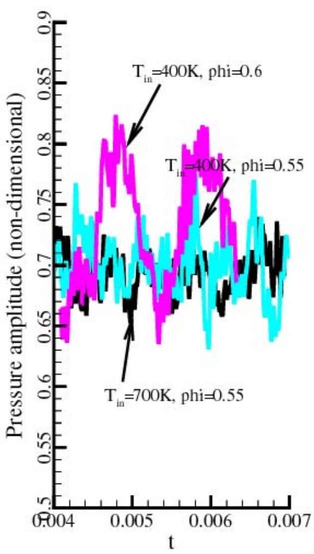

Fig. 10 Comparison of combustion chamber pressure amplitudes

CONCLUDING REMARKS

LES calculations of flame behavior in a lean premixed combustor have been presented. With the combustion model based on G-equation description, the present numerical method succeeds in reproducing phenomena of combustion instabilities.

The acoustic resonance in the combustor is captured in the present calculation and the basic resonance mode is the longitudinal quarter-wave mode. This acoustic resonance causes the flow velocity field to fluctuate leading to vortex shedding from the dump plane. The flame front shape is strongly affected by the velocity field and changed at every moment. This causes heat release fluctuations and as the Rayleigh index indicates, these three factors are interconnected with each other to sustain the unstable motion of the flame. The flame behavior is also affected by flow conditions, which implies that combustion control will be effective if it changes flow properties appropriately.

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