Combustion Instability Mechanism of a Lean Premixed Gas Turbine Combustor

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Lean premixed combustion has been considered as one of the promising solutions for the reduction of NOx emissions from gas turbines. However, unstable combustion of lean premixed flow becomes a real challenge on the way to design a reliable, highly efficient dry low NOx gas turbine combustor. Contrary to a conventional diffusion type combustion system, characteristics of premixed combustion significantly depend on a premixing degree of combusting flow. Combustion behavior in terms of stability has been studied in a model gas turbine combustor burning natural gas and air. Incompleteness of premixing is identified as significant perturbation source for inducing unstable combustion. Application of a simple convection time lag theory can only predict instability modes but cannot determine whether instability occurs or not. Low frequency perturbations are observed at the onset of instability and believed to initiate the coupling between heat release rate and pressure fluctuations.

Key Words: Combustion Instability, Gas Turbine, Lean Premixed Combustion

Nomenclature

a	: Speed of sound
C	: Concentration
D_c	: Chamber diameter
M_{inlet}	: Mach number at inlet
P	: Static pressure
p'	: Pressure fluctuation
T	: Temperature
U	: Unmixedness defined in Eq. (1)
u'	: Velocity fluctuation
X_{inj}	: Distance between dump plane and injection location
ρ	: Density
τ	: Characteristic time
ϕ	: Equivalence ratio

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1. Introduction

As legislations related to air pollution get stringent over many countries, it is more important than ever to reduce toxic emissions generated from fossil-fueled power generation systems. Moreover, a recent increase of demands for compact and convenient power generation gas turbines renders one develop and adapt "clean" power generation systems. Among the low-emission techniques developed or suggested so far, a Lean Premixed/Prevaporized (LPP) combustor is believed to be the most promising solution to provide acceptable performance in terms of combustion efficiency while also producing low pollutants (Lefebvre, 1977; Becker et al., 1986; Davis and Washam, 1989; Al Kabie and Andrews, 1990). The concept of the LPP combustor is not a recent one since it was first introduced two decades ago (Lefebvre, 1977). The relatively low flame temperature achieved at lean operating conditions results in reducing NOx production. Premixed fuel and air eliminates local fuel-rich zones in the combustor, which can eventually lead to local "hot" regions when mixed with additional air, leading to the production of thermal NO. As examples, the emissions test of a practical lean premixed gas turbine combustor burning natural gas conducted by ABB corporation (Steinbach et al., 1998) reported that NOx concentrations are reduced less than 10 ppmvd (parts per million volume dry) corrected to 15% O_2 at full load conditions up to the chamber pressures of 20 atm. Another example by a Capstone's micro gas turbine with a power rating of 30 kW shows that they decrease the amount of NOx down to 9 ppmvd@15% O_2 at full power burning natural gas (Capstone, 2000).

Even with the superior performance of pollutants reduction by a LPP combustor, it unfortunately has serious drawbacks such as flame blow-out, autoignition, and flashback, which do not appear in conventional diffusion-flame-type gas turbines with a pilot flame where fuel and air are separately introduced into the combustion chamber (Kim and Choi, 2000). Furthermore, one of serious problems is that premixed combustion at lean conditions has been sensitive to combustion instability. When premixed combustion becomes unstable, unsteady fluctuations in pressure and heat fluxes are observed to increase significantly. As a result, the fatigue of materials from mechanical vibration induced by the high amplitude of pressure fluctuations and large unsteady heat fluxes would considerably shorten the lifetime of a combustor.

One explanation for that a lean premixed combustion is susceptible to instabilities can be attributed to non uniform mixing of the inlet flows before flowing into a combustor which leads to local equivalence ratio fluctuations. It is known that even small changes in the equivalence ratio near a lean flammability limit are able to initiate large variations in many characteristics of flame such as a flame speed, a flame temperature, and a chemical time (Lieuwen et al., 1998). Also, the experimental data obtained by Zukoski (1978) show that the gradient of a chemical time grows larger as the flame becomes leaner. Since a characteristic chemical time is inversely proportional to the reaction rate, even a small change in the equivalence ratio can create large variations in the reaction rate at lean conditions compared with the stoichiometric condition. As a result, the pressure oscillations will grow stronger with definite amplitudes when the fluctuations of the reaction rate are coupled with the acoustics of the combustor system, making a closed loop of nonlinear energy exchange mechanisms.

Moreover, the assessment of the effects of premixing on combustion instability is quite important for the design of LPP combustors since the degree of premixing also affects the emission characteristics of combustors, flame structures (Fric, 1993; Lovett and Mick, 1995; Foglesong et al., 1999) and the local distributions of an equivalence ratio at a fuel nozzle. In light of these facts, the degree of premixing has been considered as a crucial parameter for a premixed combustion injector. Its effects on characteristics of combustion were investigated and its results are provided using an experimental gas turbine combustor in the present study.

2. Experiments

2.1 Combustor setup

The experimental gas turbine combustor used here in this study is burning natural gas and air at an average power rating of 96 kW(LHV) which simulates a land-based power generation gas turbine engine. The inlet air temperatures in the present study are comparable to the outlet temperatures from the compressors of actual gas turbine engines. Although the combustor has a capability of varying the chamber pressure by changing mass flow rates of air and fuel, the chamber pressure condition in this study was kept constant at 4.5 atm with a combustion air mass flow rate of 50 g/sec for all cases. For fine definition of acoustic boundary conditions, both inlet and outlet of the combustor were choked through a venturi and a nozzle, respectively. Another unique feature of this combustion chamber is that it is optically accessible even at pressurized chamber conditions. More specific description of the experimental facility can be found in Seo (1999).

For the study of extreme effects of premixing, the nearest and farthest injection locations, X_{inj}, between the dump plane and the swirler were chosen first. For simulating a fully premixed condition, fuel was injected upstream of the combustion air venturi, which should provide an enough mixing time for fuel. Two more injection locations between two extreme locations were added for more detailed study of the effects of premixing on instabilities. Since the main purpose of this study is to assess the practical application of the lean premixed combustor, the interested operating range of the overall equivalence ratio, $\phi_o=0.45\sim0.7$, stays below the stoichiometric condition. The chamber length of 235 mm gives the aspect ratio of 5.2 and the residence time between 4.9 and 6.0 msec at $T_o=670$ K and $P_c=0.458$ MPa, which were nominal operating conditions for this study. Precisely metered fuel from the fuel delivery system is drawn into the combustor through a 6.35 mm diameter stainless steel line. Depending on the injection location, X_{inj}, from the dump plane and the diameter of the injection holes, the degree of premixing and the pressure drop across the injection holes can be varied respectively.

2.2 Assessment of premixing

First, in order to assess the degree of premixing for each injection location, seeded acetone PLIF measurements were conducted in the non-reacting flows. The liquid acetone mixed with helium was fully vaporized prior to being injected into the combustion air through injection holes. The laser beam at 266 nm from the fourth harmonic generator of the Nd : YAG laser was used to excite the broadband acetone fluorescence. To increase the large field of view in the combustor, a two-dimensional laser sheet was produced by the combination of spherical and cylindrical lenses. The detection filter was WG-305 that only transmits the fluorescence signal above approximately 300 nm. Since the signal is linearly proportional to the input laser energy in the linear fluorescence regime, the averaged laser energy was also measured prior to each test, and the final data analysis was performed with the energy correction.

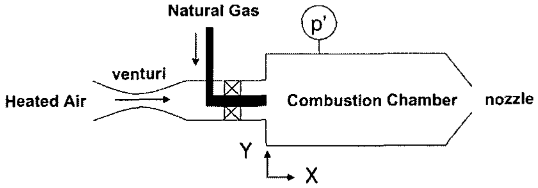

Fig. 1 Schematic of an experimental combustor. X_{inj} indicates the axial location of fuel injection

For the comparison of a premixing degree depending on the injection locations, a parameter is called unmixedness introduced using acetone PLIF results. The estimation of unmixedness, U, defined as

$$U=\frac{\overline{C'^2}}{(\bar{C}(1-\bar{C}))} \tag{1}$$

where C denotes the concentrations of acetone. The lower unmixedness values indicate the better premixing between fuel and air. Ideally, the value of unmixedness goes to one when no mixing occurs. The unmixedness is calculated based on the intensity fluctuations of single-shot acetone PLIF images and results are shown in Fig. 2. A flat curve of unmixedness at $X_{inj}=788$ mm assures that air and fuel are completely premixed for the injection before the upstream venturi. Non-zero values of unmixedness for the complete mixing case originated from the inherent fluctuations of an intensified CCD photocell, a lower detection limit, and so on. The average images of acetone

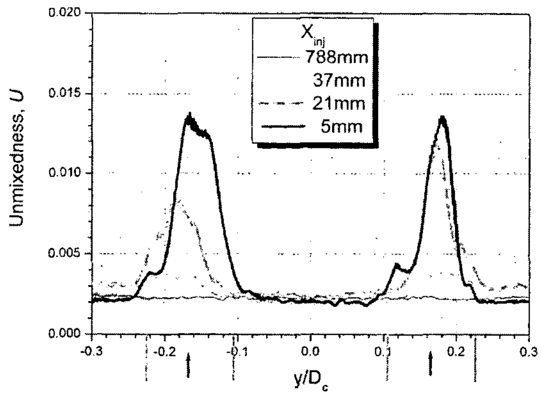

Fig. 2 Degree of mixing can be seen as a function of mixing time. Unmixedness for each X_{inj} is shown at a dump plane

PLIF (not presented here) show that the equivalence ratio fluctuations due to poor mixing become larger with the shorter X_{Inj}.

2.3 Rating of combustion stability

When combustion instability occurs, two major characteristics of combustion observed from the combustion chamber are a large heat generation and high frequency noises. Therefore, an intensity degree of dynamic pressures of a chamber can be regarded as a measure of strength of unstable combustion. Measurements of dynamic pressure using piezoelectric sensors (PCB Model 113A21) provided dynamic pressure traces and intensity of pressure fluctuations in the combustion chamber. Dynamic pressure signals were recorded when pressure oscillations reaches a limit cycle, i.e. a constant amplitude, which means that combustion becomes balanced between energy gain and loss mechanisms. Pressure oscillations sustained in the chamber were identified as resonant modes when they reached a limit cycle. Again, a normalized root-mean-square value of pressure fluctuations can be used as a measure for the intensity of unstable combustion.

3. Results and Discussion

3.1 Stability map

For each case of premixing, intensities of pressure fluctuations were measured as a function of overall equivalence ratio estimated by mass flow rates of air and fuel. Stability maps for four different premixing cases with respect to the overall equivalence ratio are plotted in Fig. 3 at the fixed inlet air temperature and chamber pressure with the swirl angle of 45 degrees.

As clearly presented in Fig. 3, combustion tends to become unstable as premixing gets worse over the range of overall equivalence ratios between 0.5 and 0.7. Obviously, the equivalence-ratio window for unstable combustion becomes narrower as the degree of premixing becomes better except the case of $U_{max}=0.014$ at which flame becomes more diffusion-like than premixed one due to a relatively short mixing time and 1 L resonant mode does not appear. Even for a fully premixed case at which equivalence ratio fluctuations due to poor mixing are believed not to exist, unstable region appears and its maximum intensity of dynamic pressures is still comparable to those of other cases at $p'_{rms}/P_c=12.5\%$. The decrease of pressure oscillations at $\phi_o=0.6$ is quite distinct for the completely premixed case at $X_{Inj}=788$ mm compared with the other injection locations. This implies that number of paths leading to instability for this fully premixed case is significantly reduced when compared to other partially premixed combustion. However, it also reveals that coupling mechanisms between heat release and acoustic of a chamber still exist due to perturbations other than local equivalence ratio fluctuations. Therefore, non uniform temporal and spatial equivalence ratio fluctuations due to poor premixing widen the window of unstable zone by inducing relatively large heat release perturbations at lean conditions. The dynamic pressure is not vanished even close to the equivalence ratio of 0.7 for the $X_{Inj}=21.0$ mm case at which local equivalence ratio distribution becomes a dominant factor in determining an unstable region.

For all conditions, the intensities of instability tend to be attenuated approaching blow-out limits. Although more chaotic perturbations in heat release are expected to occur in a leaner region, a decrease of the total amount of thermal energy generated renders pressure oscillations di-

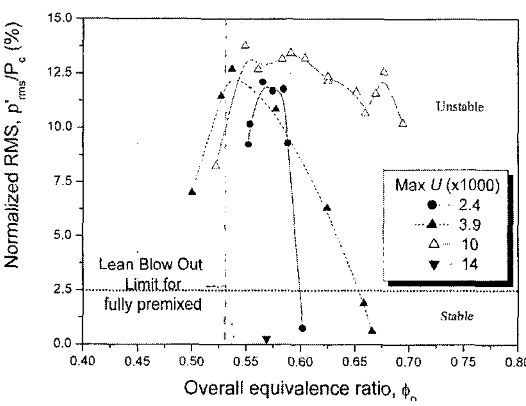

Fig. 3 Dynamic pressure oscillations as a function of an overall equivalence ratio at $T_o=670$ K and $P_c=0.458$ MPa

minish in magnitude. The poor lean blow-out limit of the completely premixed case shown in Fig. 3 might be associated with a surge of a reactant flow due to large pressure oscillations in the chamber, which prevents the continuous ignition of reactants flowing and mixing with hot product gas.

Combustion-induced instability is clearly a nonlinear phenomenon from the fact that the magnitude of pressure oscillations does not grow infinitely but reaches a certain limit. Another characteristic of this nonlinear phenomenon is also seen in its bifurcation characteristics as presented in Fig. 4. The arrows in this figure indicate the sequential direction of measurements started from two different initial conditions. Depending on an initial condition, an equivalence ratio as in this plot, the experimental output of this dynamic system may give two solutions, which means that combustion can be stable or unstable at a certain operating condition. This nonlinear characteristic of combustion instabilities should be realized when one is dealing with this issue.

3.2 Time delay for coupling

The well-known theory by Rayleigh tells that pressure oscillations get amplified when they become coupled with heat release fluctuations in phase. The time lag method according to this theory utilizes the ratio of the summation of various time scales, such as chemical time, acoustic time and convection time, to the period of oscillations as a measure of predicting conditions for coupling between heat release and resonant pressure oscillations of the chamber. To determine a value of the characteristic time ratio for coupling, it is necessary to first understand the acoustic boundary conditions of the chamber. An acoustic boundary condition of an incoming flow determines the phase difference between pressure and velocity fluctuations in the inlet section. For the present setup, the fuel flow is choked at its injection holes, and an inlet air flow is also choked through the upstream venturi. The standing normal shock forming after the upstream venturi is a strong absorber of the acoustic energy, which allows that a traveling wave propagating towards venturi is dissipated and no reflected wave exists (Crump et al., 1986). Under this assumption that the reflected wave in the inlet pipe is considered to be negligible, the relation between velocity and pressure fluctuations becomes (Dowling and Efowcs Williams, 1983)

$$u'(x, t) = -1/(\rho_0 a_0)\, p'(x, t) \qquad (2)$$

The equation indicates that the velocity fluctuations precede the pressure fluctuations by in the inlet section. Assuming that equivalence ratio fluctuations stand for heat release fluctuations at flame with considering chemical time delay negligible compared to other time scales, the following inequality for coupling of p′ and q′ can be acquired for the present experimental setup.

$$n(3/4-M_{inlet}) < \frac{\tau_{conv}}{\tau_{osc}} < N(5/4-M_{inlet}) \qquad (3)$$
$$n=1, 2, 3, \cdots$$

The plot of the time scale ratio versus the normalized dynamic pressure is presented in Fig. 5. Further assuming $M_{inlet} \ll 1$, the time scale ratios for most unsteady conditions fall into the range of 0.75 and 1.25 regardless of excited acoustic modes, 1 L and 2 L modes. Again, this assures that Rayleigh criterion holds for combustion-driven instabilities observed in this study. Two data points around $\tau_{conv}/\tau_{osc}=2.3$ come from an excited acoustic mode switching from the 1 L mode to the 2 L mode for the same

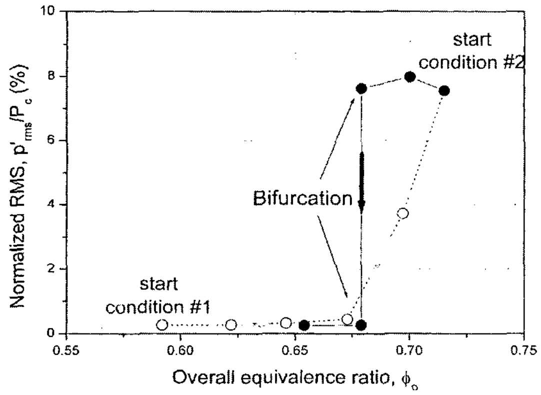

Fig. 4 Bifurcation characteristics of instabilities. Magnitude of pressure fluctuations depends on where it starts

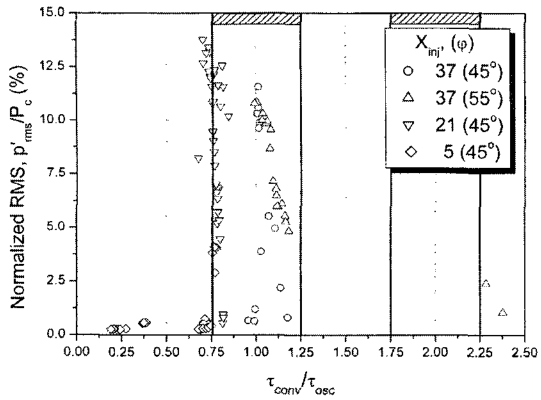

Fig. 5 Ratio of time scales demarcating in-phase and out-of-phase conditions. Shadow regions indicate time-scale-ratio windows for coupling

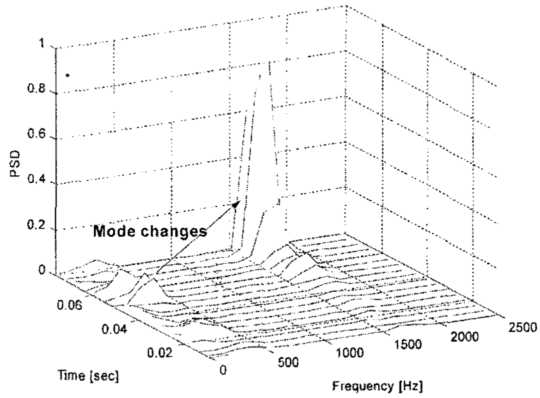

Fig. 6 Waterfall graph of dynamic pressure as a function of time at onset of instability. At the very moment of high frequency instability (~0.1 sec), a low frequency wave appears

experimental setup.

Even in the unstable region, data points with $p'_{rms}/P_c < 2\%$ can be observed. For these operating conditions, a dissipation mechanism exceeds an energy supply mechanism by coupling, which results in stable combustion. The results confirm that the Rayleigh criterion cannot predict whether instability occurs at a certain condition although it should be satisfied once flames get unsteady. This criterion is considered as not a sufficient condition but a necessary condition.

3.3 Perturbations for instability

Equivalence ratio fluctuations can originate from two different physical mechanisms. One is due to non-uniform premixing distribution of fuel and air. The other is induced by velocity fluctuations related with pressure oscillations. Therefore, total equivalence ratio fluctuations can be considered as summation of each influence like following.

$$\phi'_{total} = \phi'_{mix} + \phi'_{vel} \tag{4}$$

Equivalence ratio fluctuations due to velocity has the same wave characteristics of pressure fluctuations and equivalence ratio fluctuations due to non-uniform mixing are mainly induced from random, turbulent mixing between inlet air and fuel flows. In light of an above equation, equivalence ratio fluctuations by non uniform mixing always exist for a practical premixing flow and can induce heat release perturbation.

At onset of instability as shown in Fig. 6, low frequency wave appears and has characteristics of a bulk mode, which means that dynamic pressures in the combustion chamber are the same without phase differences. The frequency of this bulk mode is approximately 315 Hz and this value is very close to the Helmholtz frequency of the combustion chamber regarding an inlet pipe as a neck. The previous research work (Fleifil et al., 1996) shows that the flame reveals larger response to a low frequency wave than to a high frequency. These facts imply that low frequency perturbations always present in turbulent flows can trigger combustion instability even for a perfectly premixed flow.

4. Conclusions

For lean conditions, it is known that even small magnitude of equivalence ratio fluctuations can induce large fluctuations of heat release rates. As a result, the equivalence fluctuations in premixed combustion can lead to oscillations of heat release rate fluctuations that eventually couple with resonant waves in a combustion chamber, and eventually combustion instability occurs. For partially premixing conditions, the equivalence ratio fluctuations due to non uniform distribution of

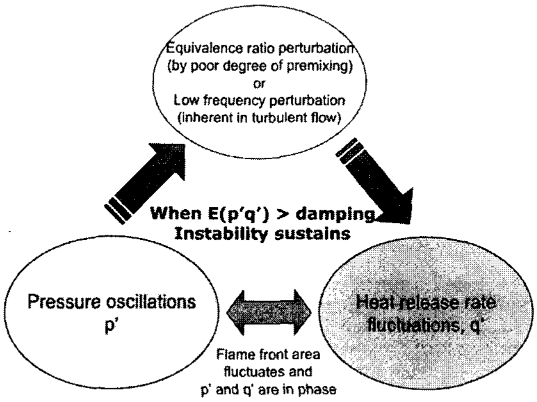

Fig. 7 Schematic shows the instability mechanism of a premixing flow of this study

degree of premixing become a main perturbation source initiating a heat release rate fluctuations. However, for fully premixed case, the flame front fluctuations due to inherent characteristics of turbulent flow induce heat release fluctuations and trigger instability. Since flame shows larger heat release response to low frequency perturbations, low frequency pressure waves become involved at the onset of instability. Once heat release fluctuations occur, combustion instability can sustain only when heat release rate and pressure fluctuations are coupled in phase and their energy exceeds dissipation mechanisms like conduction, viscosity and exit nozzle flow. This instability mechanism is described in the schematic of Fig. 7.

Lean premixed combustion instability has many unique characteristics of nonlinear dynamics such as bifurcation and limit cycle. Therefore, approach of understanding a mechanism of combustion instability can be sought through the identification of these characteristics first and then proper mechanism for each case can be established to predict and control the phenomenon occurring in actual combustion devices.

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