CONTROL OF COMBUSTION DRIVEN OSCILLATIONS BY EQUIVALENCE RATIO MODULATIONS

Christian Oliver Paschereit
ABB Corporate Research Ltd
5405 Baden
Switzerland
Email: oliver.paschereit@chcrc.abb.ch

Ephraim Gutmark
Louisiana State University
Mechanical Engineering Department
Baton Rouge, LA 70803
USA
Email: gutmark@me.lsu.edu

Wolfgang Weisenstein
ABB Corporate Research Ltd
5405 Baden
Switzerland
Email: wolfgang.weisenstein@chcrc.abb.ch

ABSTRACT

Unstable thermoacoustic modes were investigated and controlled in an experimental low-emission swirl stabilized combustor, in which the acoustic boundary conditions were modified to obtain combustion instability. Several axisymmetric and helical unstable modes were identified for fully premixed conditions. The combustion structure associated with the different unstable modes was visualized by phase locked images of OH chemiluminescence. The axisymmetric mode showed large variation of the heat release during one cycle, while the helical mode showed variation in the radial location of maximal heat release. The helical and axisymmetric unstable modes were associated with flow instabilities related to the recirculating flow in the wake-like region on the combustor axis and shear layer instabilities at the sudden expansion (dump plane), respectively. A closed loop active control system was employed to suppress the thermoacoustic pressure oscillations and to reduce undesired emissions of pollutants during premixed combustion. Microphone and OH emission detection sensors were utilized to monitor the combustion process and provide input to the control system. High frequency valves were employed to modulate the fuel injection. The specific design of the investigated experimental burner allowed testing the effect of different modulated fuel injection concepts on the different combustion instability modes. Symmetric and antisymmetric fuel injection schemes were tested. Suppression levels of up to 12 dB in the pressure oscillations were observed. In some cases a concomitant reductions of NOx and CO emissions were obtained, however, in other instances increased emissions were recorded at reduced pressure oscillations. The effect of the various pulsed fuel injection methods on the combustion structure was investigated.

INTRODUCTION

Large scale coherent structures play an important role in combustion and heat release processes by controlling the mixing between fuel and air in diffusion flame configurations and the mixing between the fresh fuel/air mixture and hot combustion products and fresh air in premixed combustors. The evolution of these structures in nonreacting flows was extensively studied in mixing layers (Oster and Wygnanski 1982, Ho and Huerrre 1984), jets (Crow and Champagne 1971, Paschereit et al. 1995) and flows over backward facing steps (Hasan, 1992). However, studies of large structures in swirling flows are scarce. Unlike large-scale structures in nonswirling flows which are predominantly axisymmetric, swirl enhances azimuthal unstable modes. Interaction between large-scale structures, which are related to flow instabilities, acoustic resonant modes in the combustion chamber and the heat release process, was shown to cause undesired thermoacoustic instabilities in the combustor. The effect of swirl on the longitudinal and azimuthal instability modes and the way it modifies the combustion process leading to thermoacoustic instabilities requires further investigation. Equivalence ratio fluctuations have been recognized as an additional mechanism driving combustion driven oscillations (Cohen et al. 1998, Peracchio and Proscia 1998, Lieuwen and Zinn 1998).

Realizing the importance of large scale structures as drivers of combustion instabilities, researchers developed passive and active methods to control this instability by modifying the vortical structures in the flow (Shadow and Gutmark 1992, McManus et al. 1993 and Anasawamy and Ghoniem 1995). Most of these control methods were applied to bluff-body-stabilized combustors and dump combustors in which the flow recirculation is used to stabilize the flame.
Passive and active control strategies have been used to suppress thermoacoustic instabilities resulting from coupling between the heat and pressure oscillations in these combustion systems (Rayleigh Criterion). Passive control strategies utilized non-circular geometries to enhance small scale mixing, reduce the coherence of large-scale vortices and to generate axial vorticity. Active control strategies utilized fuel modulations and phase-shifting to decouple the pressure and heat release cycles. Control strategies have also investigated improving fuel efficiency and reducing pollutants (Gutmark et al. 1990) and extending flammability limits (Schadow et al. 1992).

While many papers describe control of non-swirling gaseous flames, minimal amount of work was reported on control of swirling combustion. Swirl stabilization is utilized in combustion systems such as gas turbines which also exhibit combustion instabilities. Sivasegaram and Whitelaw (1991) showed that swirl reduces instability for disk-stabilized premixed gaseous flame combustion, but increased the instability for flames stabilized behind sudden expansions. Rational modification of large-scale vortices is important to control swirl induced instability and to increase combustion efficiency. However, flow control has been demonstrated primarily for non-swirling flows, in which the large-scale instabilities are well understood, and the coherence of the vortices can be enhanced by flow excitation. Control of swirling flows requires to understand the vortical structure in this type of flow and to study the effect of forcing.

Paschereit et al. (1998a, b, c, d, e, f) investigated instability modes in an experimental low-emission swirl stabilized combustor and used acoustical control methods. The two operating modes which were studied included a partially premixed-diffusion flame and premixed combustion. The diffusion flame was tuned to unstable operation with two destabilized modes, axisymmetric and helical. The premixed instability mode, which was obtained by adjusting the acoustic boundary conditions, was predominantly axisymmetric. Pressure fluctuations were detected only for the axisymmetric modes, but heat release fluctuations, which were measured by OH chemiluminescent emission, indicated dual mode behavior. The effect of acoustic excitation on the unstable combustion was investigated using upstream and downstream located loudspeakers. A closed-loop active control system was employed to suppress combustion instabilities and to reduce emissions at various operating conditions. The effect of the control system on the unstable mode structure and combustor performance was reported.

The present work extends the thermoacoustic instability control work to include a more practical (compared to acoustic excitation) fuel modulation strategy (Paschereit et al. 1999). The specific design of the experimental burner enables testing the effects of symmetric and antisymmetric fuel pulsation on the combustion instability modes. The tests were conducted with symmetric and helical instability modes. A closed loop control system was investigated and its effect on pressure and heat release oscillations and emissions was determined.

**EXPERIMENTAL SET-UP**

Combustion Facility

The combustion facility is shown in Fig. 1. The atmospheric test rig consists of a plenum chamber upstream of the swirl-inducing burner and a combustion chamber downstream of the burner. The plenum chamber contains perforated plates to reduce the turbulence level of the flow. The circular combustion chamber consists of an air-cooled double wall quartz glass to provide full visual access to the flame. The exhaust system is an air-cooled tube with the same cross-section as the combustion chamber to avoid acoustic reflections at area discontinuities. The acoustic boundary conditions of the exhaust system could be adjusted from almost anechoic (reflection coefficient |r| < 0.15) to open end reflection. An experimental swirl stabilized premixed burner was used in the experiments. The flame was stabilized in a recirculation region near the burner outlet (Paschereit et al. 1998c). The burner was operated at atmospheric conditions. Controlled excitation of the burner was achieved by modulating the premixing fuel injection using direct driven valves which have high frequency response of over 200 Hz. The specific design of the used experimental burner allowed for symmetric and antisymmetric fuel injection schemes. Two direct driven valves were mounted for this purpose and could be driven...
at 0 degrees phase difference or 180 degrees phase difference leading to a symmetric or antisymmetric excitation. Pressure fluctuations were measured using Bruel & Kjaer water-cooled microphones. Time varying heat release was recorded with a pair of filtered fiber optic probes which detected the OH radiation.

**Control System**

A closed loop feedback controller was utilized. The schematic drawing of the closed-loop control system is given in Fig. 2. The driving signal had both DC and AC components that could be independently set. The DC voltage determined the amount of continuous fuel injection, while the AC amplitude determined the amount of fuel modulations. The signals from the sensors (either microphone or OH emission probe) were amplified and band-pass filtered. The resulting signal was then used to trigger a signal generator to produce a phase shifted signal at the instability frequency which was fed-back to actuate the direct driven valves through an electronic driver. Phase locked images of the flame were obtained using an amplified (micro channel plate) CCD camera with an exposure time of 20μs. The camera was triggered by using either the pressure or OH signals which were band-pass filtered at the instability frequency and phase shifted. The images were filtered using a band-pass filtered with a low and high cutoff wavelength of 290 nm and 390 nm, respectively. The phase locked exposures were then averaged over 64 events. The operating conditions of the burner have been maintained by analyzing the exhaust gas composition using a physical gas analysis system. The nitric oxides NO and NO₂, combined in NO have been detected with a chemiluminescence analyzer. CO and CO₂ have been analyzed by using nondispersive infrared spectroscopy. The detection of the remaining O₂ in the exhaust gas was made utilizing the paramagnetic properties of oxygen in the analyzing device. Unburned hydrocarbons have been analyzed in a flame ionization detector.

**STRUCTURE OF THE INSTABILITY**

An axisymmetric thermoacoustic instability mode was forced to occur by increasing the reflection coefficient at the combustor exit (|r| > 0.5). This instability mode was related to combustion within large-scale structures which were excited in the combustion chamber due to interaction between flow instabilities and a longitudinal plane wave acoustic resonant mode in the combustion chamber. The instability was associated with the premixed mode of operation and occurred at a normalized frequency \(St = fD/U = 0.58\) where \(f\) is the instability frequency, \(D\) the burner diameter and \(U\) the burner exit velocity. A typical level of the \(St = 0.58\) was 29 dB above the background noise level. Other instabilities could be forced to occur by changing the acoustic boundary conditions and the combustion power as being discussed in Paschereit et al. (1998). The reflection coefficient \(r\) was measured by applying an extension of the two microphone method (Paschereit et al., 1998a).

The structure of the instability was visualized using an amplified and filtered CCD camera which was triggered at different phase angles relative to the instability pressure signal to obtain a sequence of phase locked images over one sequence of instability. With this technique, phase-averaged OH images were obtained for the observed thermoacoustic instability. The axisymmetric \(St = 0.58\) instability is shown in Fig. 3 at phase angles between 0 and 360 degrees every 45 degrees, for a normalized equivalence ratio of \(\phi/\phi_n = 1\), in a premixed operation. \(\phi_n\) is the nominal equivalence ratio. The visualization indicates that this instability is axisymmetric and demonstrates the variable heat release during the cycle. The lowest heat release, which is related to the OH intensity, was measured at a phase angle of 0 degrees, while the highest level was measured at 180 degrees.

**RESULTS AND DISCUSSION**

Closed-loop active control tests were performed in a premixed combustion mode by modulating the fuel injection through the premixing fuel injection ports. The tests were performed at lean equivalence ratio conditions. The fuel to air mixture ratio was varied in a range of 20% relative to the nominal operating conditions. The active control tests were performed when the combustor was destabilized in the axisymmetric mode at a normalized frequency of \(St = 0.58\). Two different fuel excitation schemes, symmetric and antisymmetric, were used to control the unstable combustion. In all tests the pressure fluctuations were monitored using a microphone which was placed near the dump plane. OH radiation was measured at a distance of \(x/D = 0.046\) from the burner exit, on the combustor centerline and in the shear layer. In all test emissions of NO₂, CO and unburned hydrocarbons (UHC) were measured in the combustor ex-
Symmetric Fuel Pulsations  The closed loop tests were conducted by monitoring the pressure fluctuations in the combustion chamber and using the recorded signal to pulse the fuel out-of-phase relative to the pressure oscillations. For symmetric fuel injection a level of pressure instability suppression of 12 dB was obtained at a fuel pulsation amplitude $F/F_{max} = 35\%$ (Fig. 4). The feedback delay phase was 180 degrees in these experiments. This optimal phase was determined in tests that measured the response to phase variation (Fig. 5). Further increase in suppression was observed for a phase of 190 degrees but the tests, which were conducted at amplitude of $F/F_{max} = 35\%$, showed an onset of a strong destabilization of the flame at phases between 190 and 360 degrees, which led to flame blow-out. Consequently, no measurements were taken in this range of phase delays. This instability was excited due to strong coupling between the symmetric fuel injection and the axisymmetric nature of the instability at $St = 0.58$. The emissions of CO and unburned hydrocarbons (Figs. 6-8) increased exponentially at this range due to the incomplete combustion during the intermittent flame destabilization and near blowout conditions. NOx emissions were reduced at phase angles between 175 and 190 due to large decrease in flame temperature near blowout (Figs. 9 and 10). At phase angles below 170 degrees both NOx and CO emissions were high compared to the uncontrolled baseline levels. The controller was tested in a range of equivalence ratios near the lean flammability limit (Fig. 11). The extent of suppres-
Figure 4. Effect of amplitude variation on pressure and OH fluctuations suppression in a closed loop controller with symmetric pulsed fuel injection (phase=180 deg.).

Figure 5. Effect of Phase variation on pressure and OH fluctuations suppression in a closed loop controller with symmetric pulsed fuel injection (amplitude $F/F_{max} = 35\%$).

Figure 6. CO emissions as a function of phase in a closed loop controller with symmetric pulsed fuel injection (amplitude $F/F_{max} = 35\%$).

Antisymmetric Fuel Pulsations

Closed-loop tests were conducted at two levels of forcing. Microphones were used as sensors to monitor the combustion instability at the symmetric mode. High amplitude forcing of $F/F_{max} = 95\%$ resulted in a range of phase delay angles between 0 and 180 degrees that induced flame blowout. Outside this range, a phase of 330 degrees suppressed the pressure oscillations by 7.5 dB (Fig. 12). At a lower amplitude forcing of $F/F_{max} = 50\%$ the flame maintained stability in the entire range of phases (Fig. 13) and yielded suppression of over 8 dB. The optimal normalized forcing level of $F/F_{max} = 50\%$ was determined in amplitude variation tests shown in Fig. 14. At this forcing level the NO\textsubscript{x} emissions were substantially decreased (Fig. 15) as well as the CO emissions (Fig. 16). The decrease in CO emission occurred at the same phase delay, which yielded optimal combustion instability suppression.

sion level decreased with the equivalence ratio until at 85\% of the nominal conditions the controlled and uncontrolled measurements were identical.
Figure 7. CO emissions as a function of amplitude in a closed loop controller with symmetric pulsed fuel injection (phase=180 deg.).

Figure 9. NO\_x emissions as a function of phase in a closed loop controller with symmetric pulsed fuel injection (amplitude F/F\_max = 35%).

Figure 8. Unburned hydrocarbons emissions as a function of amplitude in a closed loop controller with symmetric pulsed fuel injection (phase=180 deg.).

Figure 10. NO\_x emissions as a function of amplitude in a closed loop controller with symmetric pulsed fuel injection (phase=180 deg.).
Figure 11. Effect of equivalence ratio variation on pressure fluctuations suppression in a closed loop controller with symmetric pulsed fuel injection (amplitude $F/F_{max} = 35\%$, phase 180 deg.).

Figure 12. Effect of Phase variation on pressure and OH fluctuations suppression in a closed loop controller with antisymmetric pulsed fuel injection (amplitude $F/F_{max} = 95\%$).

Figure 13. Effect of Phase variation on pressure and OH fluctuations suppression in a closed loop controller with antisymmetric pulsed fuel injection (amplitude $F/F_{max} = 50\%$).

Figure 14. Effect of amplitude variation on pressure and OH fluctuations suppression in a closed loop controller with antisymmetric pulsed fuel injection (phase=330 deg.).
Figure 15. NOx emissions as a function of amplitude in a closed loop controller with antisymmetric pulsed fuel injection (phase=330 deg.).

Figure 16. CO emissions as a function of phase in a closed loop controller with antisymmetric pulsed fuel injection (amplitude $F/F_{max} = 50\%$).
SUMMARY AND CONCLUSIONS

Fuel modulations or equivalence ratio modulations were used to control thermoacoustic instabilities in an experimental swirl-stabilized gas turbine combustor. The instabilities included symmetric and helical modes. Therefore, two methods of fuel injection modulations were tested: symmetric and asymmetric injection. This control method is not only more practical than the previously tested acoustic control (Paschereit et al. 1998a, b, c) but was shown here to be more effective.

Active closed loop combustion control tests were based on microphone sensors monitoring the pressure oscillations. The tests showed that the asymmetric modulations were more effective in the suppression of the symmetric mode instability than symmetric fuel excitation. Symmetric excitation was quite efficient in abating the symmetric mode as well, however, at a certain range of phase shift the combustion was destabilized to an extent that caused blow out of the flame. In both cases the NO_x and CO emissions were increased as the pressure oscillations were lessened particularly when blow out was induced. Asymmetric fuel injection was effective in abating the symmetric mode instability providing that the modulation level did not exceed a certain level which resulted in flame blow out at certain control phase angles. At that optimal modulation level, reduction was recorded in the entire range of phase shift. Concomitant with pressure oscillation control, the emission levels of both NO_x and CO were reduced by up to 50 and 40%, respectively.

REFERENCES


