Control of Axisymmetric Combustion Instability Modes by Antisymmetric Fuel Injection

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Abstract

Unstable axisymmetric thermoacoustic modes were investigated and controlled in an experimental low-emission swirl stabilized premixed combustor, in which the acoustic boundary conditions were modified to obtain combustion instability. 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. The axisymmetric unstable modes were associated with flow instabilities related to the shear layer instabilities at the sudden expansion (dump plane). 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 antisymmetric fuel injection on the axisymmetric combustion instability mode. Suppression levels of up to 10.5 dB in the pressure oscillations were observed with a concomitant reductions of NO_x and CO emissions.

Introduction

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. Equivalence ratio fluctuations have been recognized as an additional mechanism leading to combustion driven oscillations (Cohen et al. 1998[1], Peracchio and Proscia 1998[2], Lieuwen and Zinn 1998[3]).

Realizing the importance of large scale structures as drivers of combustion instabilities, researchers developed methods to control this instability by modifying the vortical structures in the flow (Shadow and Gutmark 1992[4], McManus et al. 1993[5] and Annaswamy and Ghoniem 1995[6]). 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 combustors (Rayleigh Criterion). Active control strategies utilized fuel modulations and phase-shifting to decouple the pressure and heat release cycles.

Paschereit et al. (1998a, b, c, d, e[7, 8, 9, 10, 11]) 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. A closed-loop active control system was employed to suppress combustion instabilities and to reduce emissions at various operating conditions.

The present work extends the previous thermoacoustic instability control work to include a more practical (compared to acoustic excitation) fuel modulation strategy. The specific design of the experimental burner enables testing the effects of an antisymmetric fuel pulsation on the axisymmetric combustion instability mode. 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

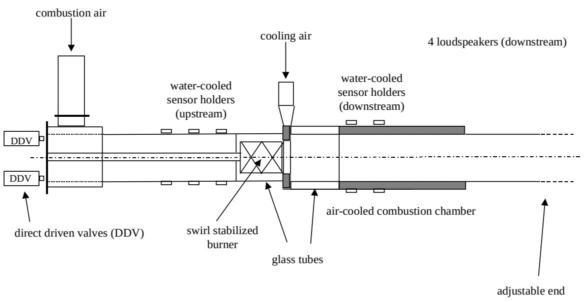

Figure 1: Experimental facility.

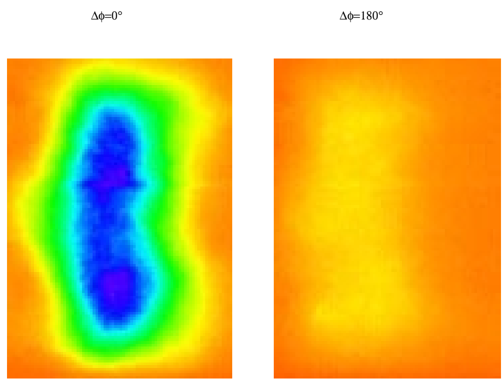

Figure 2: Phase averaged visualization of the axisymmetric low frequency instability at $St = 0.58$ at two phase angles corresponding to minimum and maximum heat release. The images were filtered using a band-pass filter at 290 nm $< \lambda <$ 390 nm and show the OH-emission of the flame.

of a plenum chamber upstream of the swirl-inducing burner and a combustion chamber downstream of the burner. The circular combustion chamber consists of an air-cooled double wall quartz glass to provide full visual access to the flame. 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. The flame was stabilized in a recirculation region near the burner outlet. Controlled excitation of the burner was achieved by modulating the premixing fuel injection using direct driven valves with high frequency response of over 200 Hz. The specific design of the used experimental burner allowed for the antisymmetric fuel injection schemes investigated in this paper. Two direct driven valves were mounted for this purpose and could be driven at 180 degrees phase difference leading to an antisymmetric excitation. Pressure fluctuations were measured using 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 signals from the sensors (either microphone or OH emission probe) were amplified, band-pass filtered, phase-shifted and 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 $20\mu s$. The images were filtered using a band-pass filtered with a low and high cutoff wavelength of 290 nm and 390 nm, respectively. 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 NO_2, combined in NO_x have been detected with a chemiluminescence analyzer.

Results and Discussion

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 $St = fD/\overline{U} = 0.58$ where f is the instability frequency, D the burner diameter and $\overline{U}$ the burner exit velocity. A typical level of the $St = 0.58$ was 29 dB above the background noise level.

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. 2 at two phase angles corresponding to maximum and minimum heat release during a single cycle, for a normalized equivalence ratio of $\phi/\phi_n = 1$, in a premixed operation. ϕ_n is the nominal equivalence ratio. The visualization indicates that this instability is axisymmetric and demonstrates the variable heat release during the cycle.

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 $St = 0.58$. Antisymmetric fuel injection was 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 NO_x and CO were measured in the combustor exhaust. Closed-loop tests were conducted

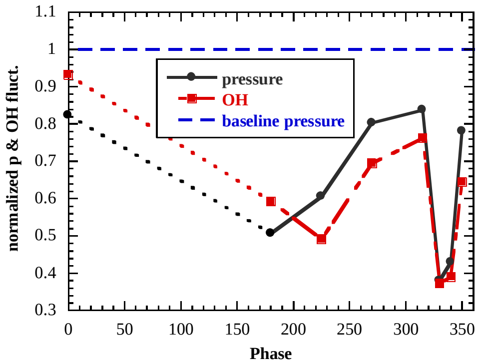

Figure 3: Effect of Phase variation on pressure and OH fluctuations suppression in a closed loop controller with antisymmetric pulsed fuel injection (amplitude $F/F_{max} = 95\%$).

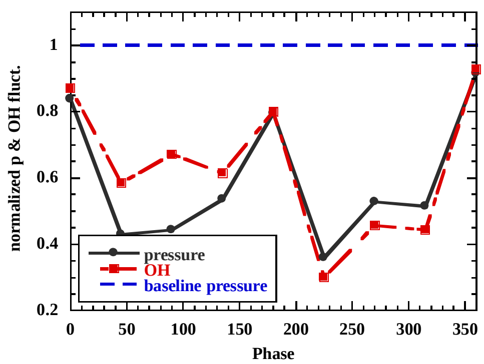

Figure 4: Effect of Phase variation on pressure and OH fluctuations suppression in a closed loop controller with antisymmetric pulsed fuel injection (amplitude $F/F_{max} = 50\%$).

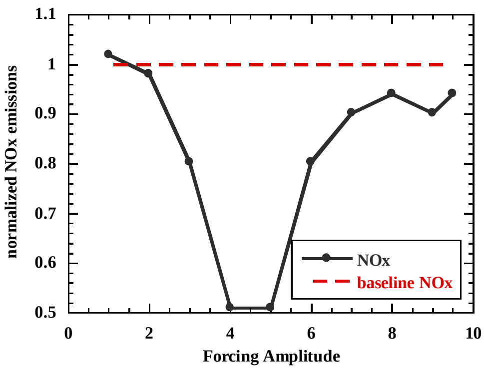

Figure 5: NOx emissions as a function of amplitude in a closed loop controller with antisymmetric pulsed fuel injection (phase=330 deg.).

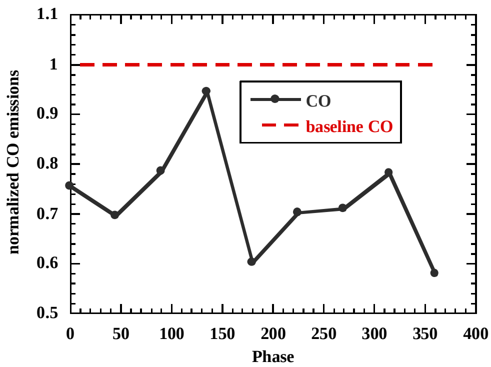

Figure 6: CO emissions as a function of phase in a closed loop controller with antisymmetric pulsed fuel injection (amplitude $F/F_{max} = 50\%$).

at two levels of forcing. 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 9 dB (Fig. 3). At a lower amplitude forcing of $F/F_{max} = 50\%$ the flame maintained stability in the entire range of phases (Fig. 4) and yielded suppression of over 10.5 dB. The optimal normalized forcing level of $F/F_{max} = 50\%$ was determined in amplitude variation tests. At this forcing level the NO_x emissions were substantially decreased (Fig. 5) as well as the CO emissions (Fig. 6). The decrease in CO emission occurred at all phase delay angles.

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, however, the present paper discussed only the control of the symmetric modes by antisymmetric fuel injection. This control method was not only more practical then 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. Asymmetric fuel injection was effective in abating the symmetric mode instability providing that the modulation level did not exceed a 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.

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