ICSV14
Cairns • Australia
9-12 July, 2007

14th
International Congress on
Sound & Vibration

ACTIVE CONTROL OF COMBUSTION INSTABILITY USING PILOT AND PREMIX FUEL MODULATION

Daniel Guyot, Matthias Rößler, Mirko R. Bothien, Christian O. Paschereit

Institute of Fluid Dynamics and Engineering Acoustics
University of Technology Berlin
D-10623 Berlin, Germany

daniel.guyot@tu-berlin.de

Abstract

Phase-shift control was applied to an atmospheric premix combustor test rig equipped with a swirl-stabilized burner. Actuation was achieved by modulating either the pilot or the premix fuel mass flow. The pilot mass flow was modulated with a standard on-off valve and a high frequency proportional valve. For premix mass flow modulation only the proportional valve was employed. The unsteady pressure signals were processed by the controller and command signals were sent to the valves. The performances of the two actuator set-ups are compared with respect to their ability to dampen thermoacoustic instability and their impact on the combustion system's emissions.

The results confirm the suitability of pilot as well as premix fuel mass flow modulation for reducing thermoacoustic instability in a lean premix combustor. Additionally, stabilizing the combustion process also resulted in reduced NO_X emissions, but on the other hand increased CO_2.

1. INTRODUCTION

Modern gas turbine technology relies on lean premixed combustion to satisfy stringent governmental emission restrictions. Premixing the fuel with large quantities of air before injecting both into the combustor significantly reduces the peak temperatures in the combustion zone and leads to lower NOx emissions.

However, combustion systems operating in the lean premixed mode are highly susceptible to the excitation of high amplitude pressure fluctuations called thermoacoustic instability (Poinsot et al. 1987 [1], Candel 1992 [2]). These self-excited oscillations are a result of the interaction between unsteady heat release in the flame and the combustion chamber's acoustic field. The main consequences of thermoacoustic instabilities are increased noise, reduced system performance and reduced system durability.

As described by Rayleigh's Criterion (1945 [3]), self-excitation of a combustion system occurs if the fluctuations in heat release from the combustion process are in phase with the pressure fluctuations. Although the real instability processes are somewhat more complex (due to combustor dynamics, fluid dynamics, chemical kinetics, transport processes, flame kinematics, heat transfer, etc.), Rayleigh's Criterion pinpoints how control of thermoacoustic instability can be achieved. A common approach is to induce heat release fluctuations, which are out of phase with the pressure fluctuations.

Passive techniques were developed to control the combustion characteristics by modifications of the fuel distribution pattern and changes in the combustor geometry (Schadow and Gutmark 1992 [4]). Active control systems, which have the potential to be more adaptable to variable operational conditions, decouple the physical processes that excite combustion instabilities, such as mixing, acoustics, and heat release. They acquire sensors, actuators, and feedback control algorithms that are used to drive the actuators and process output from the sensors. The actuators are used to modulate the air or fuel supply into the combustor. Dowling and Morgans (2005 [5]) completed an extensive review of active control.

Unsteady fuel injection was investigated as an actuation method for control systems that can potentially be adopted in full-scale power generation or propulsion applications. Langhorne et al. (1990 [6]) demonstrated active control of a 250 kW ducted flame. They obtained a 12 dB reduction in peak pressure oscillations by injecting 3% additional unsteady fuel upstream of the flame holder. Closed loop active control of instabilities in a 500 kW dump combustor using modulated liquid fuel injection was reported by Yu et al. (1996 [7]). They emphasized the importance of the injection timing of the modulated fuel relative to the formation of air vortices during instability on the droplets dispersion. McManus et al. (1998 [8]) modulated the main fuel flow using a high speed solenoid valve in an open loop and closed loop control system aimed to study combustion instabilities in a simulated afterburner. Their experiments showed strong response of the combustion process to the fuel modulations. Secondary fuel modulation was also shown to be effective in reducing combustion instabilities in gas turbine combustors (Cohen et al. 1998 [9]).

Paschereit et al. (1999 [10, 11]) investigated active control methods to suppress combustion instabilities in a swirl stabilized burner. They incorporated symmetric and asymmetric fuel as well as equivalence ratio modulation into their open loop and closed loop control schemes and not only achieved instability attenuation but simultaneously reduced emissions.

Moeck et al. (2006 [12]) applied pilot fuel mass flow modulation by means of an on-off valve to the same combustion test rig also used for the present work (with slight modifications). They proofed the efficiency of pilot modulation to damp an acoustic instability in this test rig. However, no study of the controller's impact on emissions was performed.

In the present work, phase-shift control was applied to an atmospheric premix combustor test rig equipped with a generic swirl-stabilized burner. Actuation was achieved by modulating either the pilot or the premix fuel flow. Pilot fuel modulation strategy was tested with a standard on-off valve and a high frequency proportional valve. Premix fuel modulation was achieved using the high frequency proportional valve. Condenser microphones were employed to record the pressure oscillations inside the combustion chamber. The microphone signals were processed by the controller and command signals were sent to the valves. The performances of the different actuator set-ups was investigated with respect to their ability to dampen thermoacoustic instability and their impact on the combustion system's emissions.

2. EXPERIMENTAL SET-UP

2.1. Combustion Facility

All measurement results presented in this paper were obtained using the combustion facility depicted in Fig. 1. The atmospheric low-emission combustor had a 300 mm long, air-cooled quartz glass combustion chamber allowing for optical access to the flame. To generate a thermoacoustic instability with a frequency close to those typically occurring in full-scale engines, a water-cooled resonance tube of 1500 mm total length, was attached to this combustion chamber. The resonance tube consisted of three parts mounted together by flanges, the middle part was equipped with five water-cooled microphone holders and the downstream part with two speakers allowing for acoustic excitation.

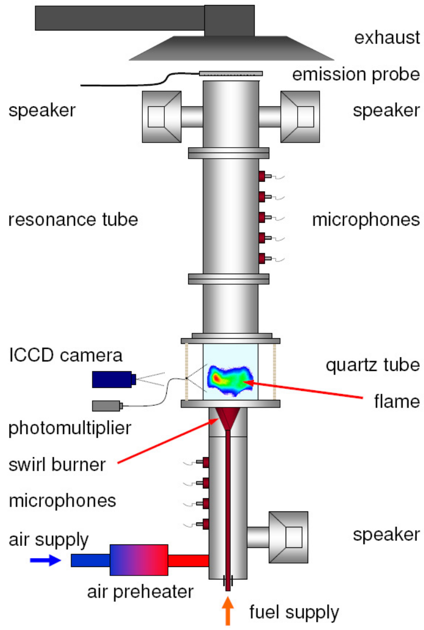

Figure 1. Combustion test facility

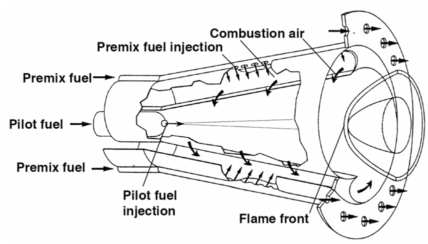

Figure 2. ABB EV-10 burner

The combustor incorporated a generic environmental burner (EV-10) designed by ABB with a cross-sectional area expansion ratio of 4 for flame stabilization. Figure 2 shows a detailed sketch of the burner. It is composed of two half cones shifted in such a way that the air is forced to enter the cone circumferentially through two slots. The resulting swirling airflow generates a recirculation zone along the centerline at the burner outlet, thus stabilizing the flame in this region. In standard operation (i.e. without fuel mass flow modulation), the main (premix) fuel is injected through 62 boreholes, 0.7 mm in diameter each, which are distributed equidistantly along the burner's two air slots and fed from one common fuel supply. Mixing of swirling air and main fuel results in a nearly premixed combustion. Pilot fuel can be injected at the EV-10 cone apex using a pilot lance. For a detailed description of the burner see [13].

2.2. Sensors

Pressure oscillations in the combustion chamber were measured using a condenser microphone placed into the upstream microphone holder of the resonance tube. The heat release oscillation was measured using a photomultiplier equipped with narrow band-pass filter centered at 308 nm. At this wavelength, the photomultiplier captured light from OH* chemiluminescence, which is proportional to the heat release [14]. The microphone and photomultiplier signals were amplified and low-pass filtered at 2 kHz to avoid aliasing.

The emission analysis system captured the exhaust gases of the combustor through an emission probe positioned at resonance tube's exit cross section. The distances between the probe's inlet holes were area-weighted to account for different emission concentrations at different radii. The concentrations of NO, NO_2, CO, CO_2 and O_2 were measured. The recorded emission data was at all times normalized with the emissions at baseline conditions (no actuation).

2.3. Phase-shift Control Schemes

To allow for control of combustion instability the pilot or the premix mass flow were modulated by valves. Two different types of valves were tested: 1) *Standard on-off valve* – A Bosch injection valve, commonly used in the automobile industry for the injection of gaseous fuel. This valve featured an on-off characteristic with a duty cycle of 4 ms. 2) *A high frequency proportional valve* – A Moog D633 DDV servo-proportional control valve capable of modulating the through flow at frequencies of up to 400 Hz.

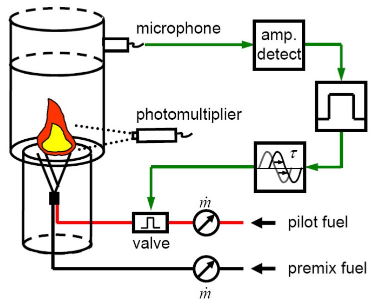

Figure 3. Phase-shift control using the on-off valve in the pilot fuel line.

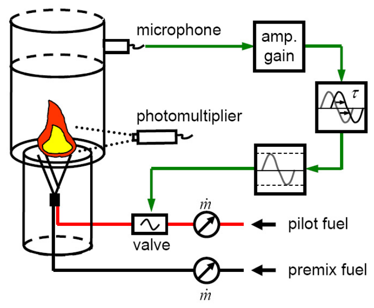

Figure 4. Phase-shift control using the proportional valve in the pilot fuel line.

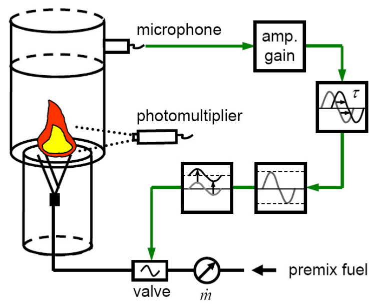

Figure 5. Phase-shift control using the proportional valve in the premix fuel line.

Figures 3 and 4 show a schematic sketch of the control set-up for pilot mass flow modulation using the on-off valve and the proportional valve, respectively. Fig. 5 presents the corresponding set-up for premix mass flow modulation using the proportional valve. The mean premix and pilot mass flows were measured and controlled by two mass flow controllers, each of them consisting of a coriolis flow meter and a slow-response proportional valve. The on-off and high-frequency proportional valve were placed into the pilot or premix fuel line downstream of the mass flow controller, directly upstream of the pilot fuel lance.

For closed loop control, the pressure oscillations recorded by the microphone served as input to the controller. In principal, the heat release signal could also have been used as the controller input, but it usually contains more noise. The reason for placing the microphone into the microphone holder closest to the flame was that it detected a higher amplitude at this position due to the quarter-wave mode shape.

In the feedback loop, a Matlab/Simulink program running on a dSPACE board processed the incoming pressure signal. The control board ran at a sampling frequency of 10 kHz. In the case of the on-off valve (see Fig. 3), the control program detected every zero-crossing with positive slope (rising edge) of the pressure signal. For each detected rising edge the controller generated a trigger pulse. This pulse was phase-shifted and then passed to the on-off valve. The on-off valve was thus operating at the fundamental frequency of the pressure oscillations. A detailed description of this program is given in [12].

In case of the proportional valve modulating the pilot mass flow (see Fig. 4), the incoming pressure signal was first amplified and phase-shifted. To ensure that the output amplitude of the controller did not exceed the operation range of the Moog valve, the output signal was saturated before being sent to the Moog valve. This saturation, however, did not cut off the controller signal at a certain amplitude, but reduced the amplitude of the whole signal. For premix mass flow modulation (see Fig. 5), an off-set was added to the Moog command signal, so that only a certain percentage of the mean fuel flow was modulated.

The input signal to the controller was not band-pass filtered with a filter centered at the fundamental instability frequency. Although using a narrow band-pass filter on the input signal can help to track the dominant mode, such a filter generally induces a rapid phase change along the passband and adversely affects the control scheme if the frequency of oscillation is shifted by the controller. This mechanism can cause an intermittent loss of control [15].

3. OPERATING CONDITIONS

All combustion tests were conducted with an air mass flow of 200 kg/h entering the burner at a temperature of 300 K, natural gas as fuel, and an overall equivalence ratio of 0.74. At baseline conditions (no fuel modulation, no pilot fuel) this operating point corresponded to a strong instability with high pulsation amplitudes. Although control efficiency at one operating point cannot be considered representative for all possible sets of parameter combinations, this operating point was the most demanding in terms of actuator authority.

Figure 6 shows the spectra of the pressure and heat release oscillation recorded at baseline conditions. Both signals exhibit a dominate peak at 87 Hz, that corresponds to the quarter wave mode of the tubes downstream of the burner. Harmonics are also clearly visible in the pressure as well as in the heat release signal.

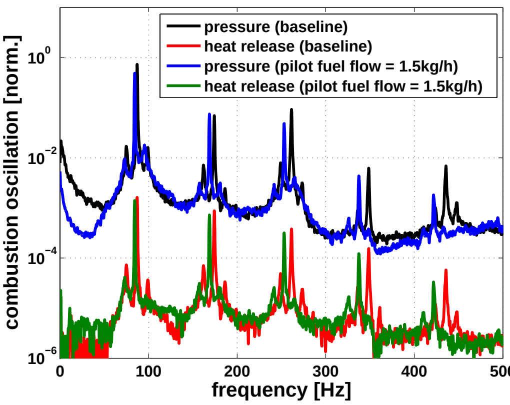

Figure 6. Spectra of pressure and heat release oscillations at baseline conditions and for a constant pilot mass flow of 1.5 kg/h.

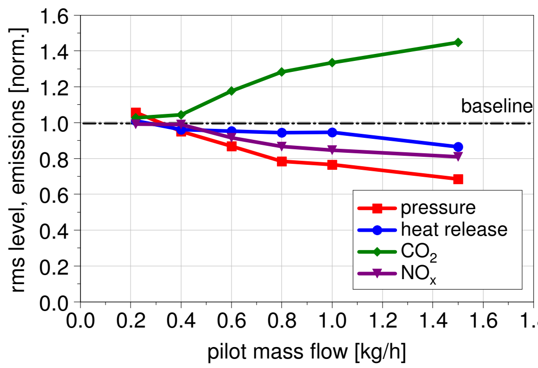

Figure 7. Effect of steady pilot fuel injection on combustion oscillation and emissions.

Before applying phase-shift control to the combustion system, the influence of steady pilot fuel injection was investigated. The gas mass flow through the pilot lance was increased, while the overall fuel mass flow (and hence the equivalence ratio) was kept constant. The pressure and heat release trends as well as NO_X and CO_2 emissions are presented in Fig. 7. Note that CO emissions were in the order of 1 ppm for all operating conditions presented in this paper. Note also that the rms and emission results are normalized with respect to baseline conditions in all cases.

Fig. 7 shows a reduction of NO_X of up to 20 % and an increase in CO_2 of up to approximately 45 % as the pilot fuel was increased. At stable combustion, one would expect NO_X to increase with pilot fuel flow, because of the higher temperature in the more diffusion like pilot flame. Here, however, steady pilot injection had a stabilizing effect on the premixed flame. This effect was also reported in [16]. The observed trend in NO_X is likely due to the non-linear dependence of NO_X formation on the equivalence ratio, i.e., a reduction in combustion oscillation (in pressure and hence in equivalence ratio) causes a NO_X reduction as the pilot fuel is increased. The increase in CO_2 can be explained by the higher equivalence ratio in the pilot flame. The higher the pilot mass flow, the more CO_2 is generated. For a steady pilot mass flow of 1.5 kg/h the spectra of the corresponding pressure and heat release oscillations are plotted in Fig. 6 together with the spectrum at baseline conditions. As to be expected from the rms results, the baseline amplitudes are slightly higher than the ones at steady pilot fuel injection.

4. PHASE-SHIFT CONTROL USING PREMIX FUEL MODULATION

This section presents the results obtained for phase-shift control achieved by pilot fuel modulation. The influence of time-delay and mean pilot mass flow on thermoacoustic instability suppression was studied.

4.1. Pilot fuel modulation with the on-off valve

For actuation with the on-off valve, Fig. 8 presents the normalized levels of pressure and heat release rms as well as NO_X and CO_2 as a function of time-delay. The mean pilot fuel flow was 0.5 kg/h. The time-delay was first set to zero and then increased in steps of 0.6 ms to a maximum time-delay of 12.6 ms. A phase-shift of 360° with respect to the dominant oscillation frequency at baseline conditions (87 Hz) corresponds to a time-delay of 11.5 ms.

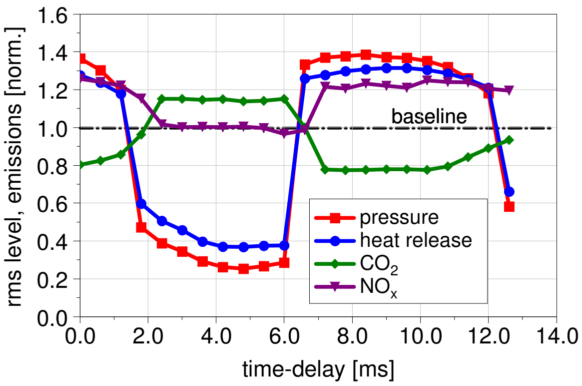

Figure 8. Combustion oscillations and emissions vs. time-delay for a mean pilot fuel flow of 0.5 kg/h modulated by the on-off valve.

Regarding the influence of time-delay on combustion oscillation, suppression was achieved for time-delays between 1.8 and 6.0 ms with a maximum attenuation in pressure of 75 % (12 dB) at 4.8 ms. Slightly shorter or longer time-delays immediately resulted in amplification of the combustion oscillations above baseline conditions. Maximum amplification in pressure of 38 % (2.8 dB) was recorded at 7.8 and 8.4 ms time-delay.

The emission trends also show the impact of instability amplification and damping. In case of unfavorable control, NO_X rose by approximately 23 %, while CO_2 was reduced by 23 %. In contrast, when suppressing the instability, CO_2 was increased and NO_X matched with baseline conditions. These trends agree with the argumentation given for the explatation of the emission trends in Fig. 7. The only difference is that NO_X is not reduced below baseline conditions for the mean pilot mass flow investigated here. The spectra of the pressure signals for maximum suppression ($\Delta\tau$= 4.8 ms) and maximum amplification ($\Delta\tau$= 7.8 ms) are plotted in Fig. 9 together with the baseline spectrum.

The dependence of combustion oscillations and emissions at maximum instability attenuation ($\Delta\tau$= 4.8 ms) on the pilot fuel flow is illustrated in Fig. 10. In contrast to constant pilot fuel injection, instability suppression using modulated pilot fuel injection achieved higher suppression levels and lower NO_X emissions at smaller pilot fuel flows. Also the CO_2 emissions reduced as the mean pilot fuel flow was decreased.

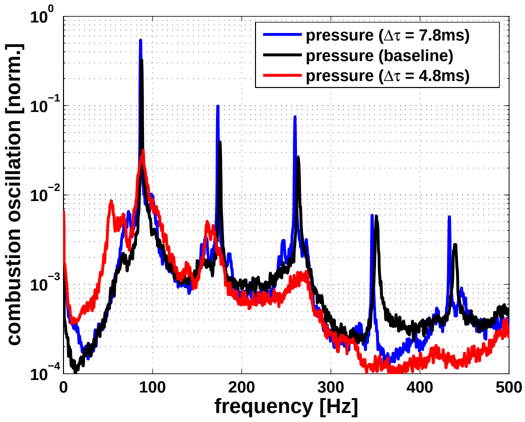

Figure 9. Pressure spectra for maximum instability suppression, maximum instability amplification, and at baseline conditions for 0.5 kg/h mean pilot fuel flow.

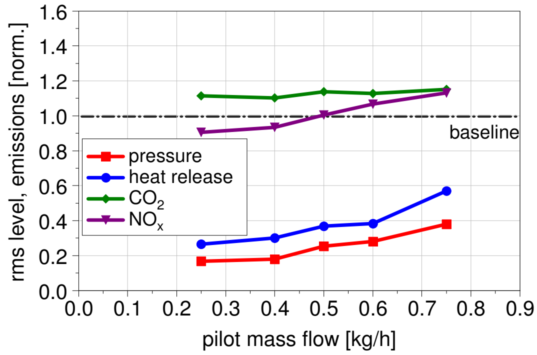

Figure 10. Combustion oscillations and emissions vs. pilot fuel flow modulated by the on-off valve at a time-delay of 4.8 ms.

4.2. Pilot fuel modulation with the proportional valve

To study the effect of pilot fuel modulation proportional to the time history of the combustion oscillation, the on-off valve in the pilot fuel line was replaced by the Moog valve (see Fig. 4). The control program was modified to modulate the pilot mass flow proportional to the pressure oscillations.

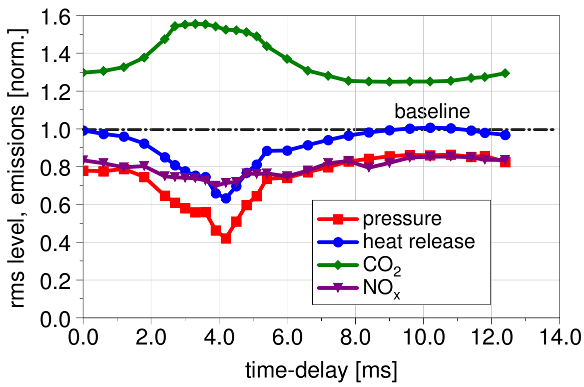

Figure 11. Combustion oscillation and emissions vs. time-delay for a mean pilot fuel flow of 1.0 kg/h modulated by the Moog valve.

In Fig. 11 the pressure and heat release rms and emissions are presented. The mean pilot fuel flow was 1.0 kg/h. Although highest instability suppression occurred for much smaller pilot mass flows when using the on-off valve, a mass flow of 1.0 kg/h was chosen here, given that for smaller mass flows only minor effects of the phase-shift on the combustion oscillations were observed. This was probably due to the fact that the modulation signal forced onto the pilot flow smeared out while the fuel was passing through the tubing and the pilot lance.

This assumption is supported by hot wire anemometry measurements, in which the velocity fluctuations downstream of both valves (on-off and proportional) were first measured directly at the valves' exits and then at the exit of a 100 cm tube attached to the valves. For both types of valve a smearing out effect was observed. However, for sinusoidal mass flow modulation generated by the proportional valve, the constant component of the velocity oscillations at the tube's exit was much higher.

In contrast to phase-shift control with the on-off valves, the controlled pressure oscillations in Fig. 11 are smaller than in the baseline case for all phase-shifts. However, the maximum suppression of 58 % (7.5 dB) occured at $\Delta\tau$= 4.2 ms is smaller then that with the on-off valves. Also, the change from high to low rms levels occures more gradually than for on-off modulation, though the minimum in the rms curves is more pointy compared to Fig. 8. Generally, one would expect that generating additional heat release fluctuations in phase with the instability should amplify the pressure oscillations, as was observed for pilot fuel modulation with the on-off valve. However, as shown in the previous section, steady pilot injection already has a stabilizing effect on the premixed flame. Considering the smearing out of the pilot mass flow modulation mentioned above, the results here suggest that the stabilizing effect of the pilot injection's constant component is dominant compared to the amplifying effect of heat release in phase with the pressure oscillations.

Like the pressure rms, NO_X is always below baseline conditions with a reduction of up to 30 % at time-delays corresponding to highest instability suppression, while CO_2 is always above the baseline level with the highest emissions within the range of strong instability suppression.

5. PHASE-SHIFT CONTROL USING PREMIX FUEL MODULATION

To investigate whether premix fuel modulation is also effective in instability suppression, the Moog valve was placed into the premix fuel line. Here, it modulated a certain percentage of the fuel flow. The Moog valve was set to modulate 20 % of the overall fuel flow and the time-delay was varied as in the phase-shift experiments for pilot fuel modulation.

The results for pressure and heat release rms and emissons are shown in Fig. 12. Although maximum suppression of the pressure pulsations was only 2.5 %, the pressure and heat release trends clearly indicate that the time-delay for maximum suppression is 10.8 ms. The relatively small impact of 20 % premix fuel modulation on the combustion oscillation is thought to be due to the high damping of the modulation amplitude in the premix lance and especially across the premix injection holes.

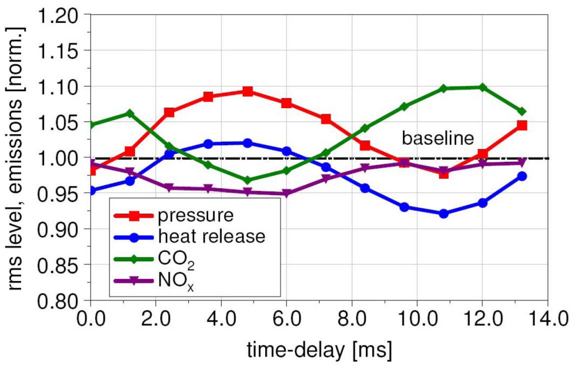

Figure 12. Combustion oscillations and emissions vs. time-delay for 20 % of premix fuel modulation.

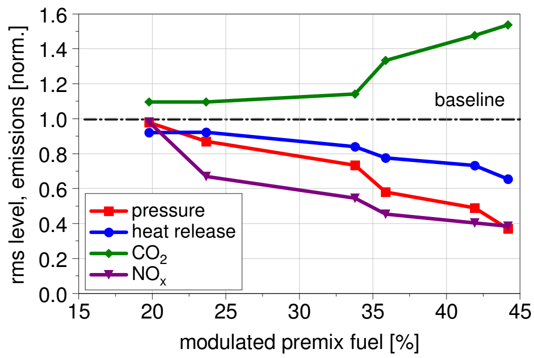

Figure 13. Combustion oscillations and emissions vs. percentage of modulated premix fuel flow at a time-delay of 10.8 ms.

At 10.8 ms time-delay, the actuation amplitude of the valve, and hence the percentage of modulated fuel, was increased. The effect on combustion oscillation and emissions is presented in Fig. 13. In contrast to pilot fuel modulation, increasing the amplitude of the premix fuel modulation reduced the pressure rms. The maximum suppression achieved was 63 % (8.6 dB) for 44 % of modulated fuel. Further increase of the actuation amplitude, however, caused blow out of the flame.

As for instability suppression obtained with modulated pilot injection, NO_X decreased with lower pressure oscillation levels. The maximum reduction was 60 %. CO_2 increased with reduced pressure oscillations by up to 52 % with respect to baseline conditions. The fact that the NO_X benefit for similar suppression levels of pressure pulsations is higher for premix fuel modulation than for pilot fuel modulation can be attributed to the lack of a pilot flame in the former case.

6. SUMMARY AND CONCLUSION

Active instability control was applied to an atmospheric swirl-stabilized premixed combustor using phase-shift control. Actuation was achieved by either pilot or premix fuel modulation using an on-off valve or a high-frequency proportional valve. The proportional valve was tested in the pilot and premix fuel modulation scheme, whereas with the on-off valve only the pilot fuel was modulated. Pressure and heat release oscillations as well as NO_X, CO, CO_2 and O_2 emissions were recorded. CO emissions were approximately 1 ppm for all operating points, indicating almost complete combustion.

It was shown that steady pilot fuel injection had a stabilizing effect on the premixed flame. Regarding emissions, the general observation for all control methods tested was that instability suppression also lead to a reduction of NO_X emissions, while CO_2 emissions increased. On the other hand, instability amplification was accompanied by a rise in NO_X and decreasing CO_2 emissions. The NO_X trends were linked to the non-linear dependence of NO_X formation on equivalence ratio fluctuations.

For pilot fuel modulation highest instability suppression was achieved using the on-off valve with a maximum damping of 12.0 dB. The variation of the phase-shift revealed a phase-shift range, where suppression, and a phase-shift range, where amplification of the pressure and heat release oscillation occurred. The change-over between these two regions had a very steep slope, while within one region the difference, e.g. in pressure rms levels, between two different phase-shifts was only small. This behavior could raise difficulties for the application of adaptive control strategies like extremum seeking control.

For pilot fuel modulation using the proportional valve, the change-over between phase-shifts with high and low instability suppression was much more gradual. However, for all phase-shifts the recorded pressure pulsations were smaller than in the baseline case. This effect is thought to be due to the smearing out of the modulation amplitude in the pilot fuel flow, which leads to a high constant component of the pilot injection. The stabilizing effect of this steady fraction of the pilot injection is thought to be more dominant compared to the amplification of the heat release in phase with the pressure oscillations.

Premix fuel modulation required much higher modulation amplitudes to have an impact on the combustion process, most likely also due to a smearing out effect and the pressure drop across the burner's injection holes. For similar instability suppression levels, premix fuel modulations showed a higher NO_X and larger increase in CO_2 emissions.

REFERENCES

[1] Poinsot, T. J., Trouve, A. C., Veynante, D. P., Candel, S. M., and Esposito, E. J., 1987. "Vortex-driven acoustically coupled combustion instabilities". *J. Fluid Mech.,* **177**, pp. 265–292.

[2] Candel, S. M., 1992. "Combustion instabilities coupled by pressure waves and their active control". 24th Symposium (International) on Combustion, The Combustion Institute, pp. 1277–1296.

[3] Rayleigh, J. W. S., 1945. *The Theory of Sound*, Vol. 2. Dover Publications, New York.

[4] Schadow, K. C., and Gutmark, E., 1992. "Combustion instability related to vortex shedding in dump combustors and their passive control". *Progress in Energy and Combustion Science,* **18**, pp. 117–132.

[5] Dowling, A. P., and Morgans, A. S., 2005. "Feedback Control of Combustion Oscillations". *Annu. Rev. Fluid Mech.,* **37**, pp. 151–82.

[6] Langhorne, P. J., Dowling, A. P., and Hooper, N., 1990. "Practical active control system for combustion oscillations". *Journal of Propulsion and Power,* **6**, pp. 324–333.

[7] Yu, K., Wilson, K. J., Parr, T. P., Schadow, K. C., and Gutmark, E. J., 1996. "Active control of liquid fueled combustion using periodic vortex-droplet interaction". In 26th International Symposium on Combustion, The Combustion Institute.

[8] McManus, K. R., Magill, J. C., and Miller, M. F., 1998. "Combustion instability suppression in liquid fueled combustors". In 36th Aerospace Sciences Meeting, no. AIAA Paper 98-0642.

[9] Cohen, M. F., Rey, N. M., Jacobsen, C. A., and Anderson, T. J., 1998. "Active control of combustion instability in a liquid - fueled low-NOx combustor". In ASME Turbo Expo '98, no. ASME Paper 98-GT-267.

[10] Paschereit, C. O., Gutmark, E., and Weisenstein, W., 1999. "Acoustic and fuel modulation control for reduction of thermoacoustic instabilities". In Fourteenth International Symposium on Airbreathing Engines.

[11] Paschereit, C. O., Gutmark, E., and Weisenstein, W., 1999. "Control of combustion driven oscillations by equivalence ratio modulations". In ASME Turbo Expo '99.

[12] Moeck, J. P., Bothien, M. R., Guyot, D., and Paschereit, C. O., 2006. "Phase-Shift Control of Combustion Instability Using (Combined) Secondary Fuel Injection and Acoustic Forcing". Conference on Active Flow Control.

[13] Döbbeling, K., Knöpfel, H. P., Polifke, W., Winkler, D., Steinbach, C., and Sattelmayer, T., 1994. "Low NOx Premixed Combustion of MBtu Fuels Using the ABB Double Cone Burner (EV Burner)". ASME Paper 94-GT-394.

[14] Haber, L. C., Vandsburger, U., Saunders, W. R., and Khanna, V. K., 2000. "An Examination of the Relationship between Chemiluminescent Light Emission and Heat Release Rate under Non-adiabatic Conditions". ASME Paper 2000-GT-0121.

[15] Yu, K. H., Wilson, K. J., and Schadow, K. C., 1998. "Liquid-Fueled Active Instability Suppression". 27th Symposium (International) on Combustion, The Combustion Insitute, pp. 2039–2046.

[16] Paschereit, C. O., Gutmark, E., and Weisenstein, W., 1999. "Control of thermoacoustic instabilities in a premixed combustor by fuel modulation". In 37th AIAA Aerospace Science Meeting and Exhibit, no. AIAA Paper 99-0711.