TITLE: Performance Enhancement of Gas-Turbine Combustor by Active Control of Fuel Injection and Mixing Process - Theory and Practice

TITLE: Active Control Technology for Enhanced Performance Operational Capabilities of Military Aircraft, Land Vehicles and Sea Vehicles [Technologies des systemes a commandes actives pour l'amelioration des performances operationnelles des aeronefs militaires, des vehicules terrestres et des vehicules maritimes]

Performance Enhancement of Gas-Turbine Combustor by Active Control of Fuel Injection and Mixing Process—Theory and Practice

Christian Oliver Paschereit*
ALSTOM POWER Ltd, AAT-T4 5405 Baden, Switzerland

Ephraim Gutmark†
University of Cincinnati, Aerospace Engineering and Engineering Mechanics Dept.
797 Rhodes Hall, P.O. Box 210070, Cincinnati OH 45221-0070, USA

Bruno Schuermans‡
ALSTOM POWER Ltd, AAT-T4 5405 Baden, Switzerland

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. Axisymmetric and helical unstable modes were identified for fully premixed combustion. These unstable modes were associated with flow instabilities related to the recirculation region on the combustor axis and shear layer instabilities at the sudden expansion (dump plane). 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 modes showed circumferential variations in the location of maximal heat release. Two feedback control methods employed to suppress thermoacoustic pressure oscillations and to reduce emissions are reviewed: proportional acoustic control and fuel modulations. Microphone sensors monitored the combustion process and provided input to the control systems. An acoustic actuation modulated the airflow and thus affected the mixing process and the combustion. Suppression levels of up to 25 dB in the pressure oscillations and a concomitant 10% reduction of NO_x emissions were obtained. At the optimal control conditions it was shown that the major effect of the control system was to reduce the coherence of the vortical structures which gave rise to the thermoacoustic instability. The specific design of the investigated experimental burner allowed testing the effect of different modulated fuel injection concepts on the 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 concomitant reductions of NO_x and CO emissions were obtained. Open loop control of low frequency symmetric instability by secondary fuel injection in a pilot flame reduced the pressure oscillations by up to 20 dB.

Introduction

The initial shear layer of a swirling mixed air and fuel jet exiting a burner in a swirl-stabilized combustor undergoes Kelvin-Helmholtz instability. This instability causes the shear layer to roll-up into vortical coherent structures which affects the jet's growth rate by entrainment of ambient fluid and by mixing it with the jet's fluid. Therefore, these vortices play an important role in the combustion and heat release processes by controlling the mixing between the fresh fuel/air mixture and hot combustion products and fresh air in premixed combustors. The initiation and evolution of these structures in nonreacting flows was extensively studied in mixing layers (Oster and Wygnanski 1982,[1] Ho and Huerre 1984[2]), jets (Crow and Champagne 1971,[3] Paschereit et al. 1995[4]) and flows over backward facing steps (Hasan, 1992[5]). 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 (Paschereit et al. 1999,[6] Schuermans et al. 1999[7]). 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.

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 (Schadow and Gutmark 1992,[8] McManus et al. 1993[9] and Annaswamy and Ghoniem 1995[10]). Most of these control methods were applied to bluff-body-

---

*Email: oliver.paschereit@ch.abb.com
†Email: egutmark@uceng.uc.edu
‡Email: bruno.schuermans@ch.abb.com

Paper presented at the RTO AVT Symposium on "Active Control Technology for Enhanced Performance Operational Capabilities of Military Aircraft, Land Vehicles and Sea Vehicles", held in Braunschweig, Germany, 8-11 May 2000, and published in RTO MP-051.

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). 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[11]) and extending flammability limits (Schadow et al. 1992[12]).

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[13]) 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 influenced by flow excitation. Control of swirling flows requires an understanding of the vortical structure in this type of flow and an understanding of the effect of forcing.

Paschereit et al. (1998a, b, c, d, e, f, 1999[14–20]) 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.

Paschereit et al. (1999[21,22]) extended the thermoacoustic instability control work to include a more practical (compared to acoustic excitation) fuel modulation strategy. Symmetric and antisymmetric fuel pulsations were used to control symmetric and helical instability modes. Open and closed loop control systems that modulated either the premixed or the pilot fuel injection were shown to suppress effectively pressure and heat release oscillations and reduce emissions. The present review summarizes this work.

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. The flame was stabilized in a recirculation region near the burner outlet. The burner was operated at atmospheric conditions. Two methods of actuation were investigated: acoustical and fuel modulations. Acoustic controlled excitation of the burner flow was accomplished by a circumferential array of four loudspeakers equally spaced in polar angle.

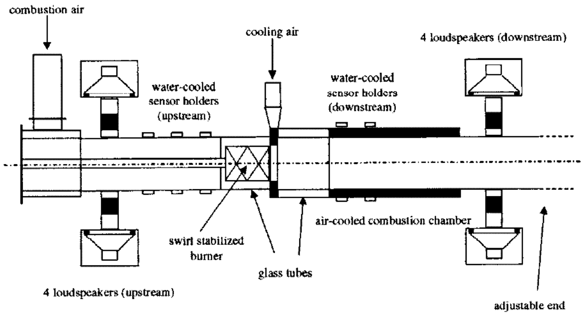

Fig. 1 Experimental facility

Premixed fuel injection modulation was obtained by using direct driven valves which have high frequency response of over 200 Hz. The specific design of the experimental burner allowed for symmetric and antisymmetric fuel injection schemes. Pressure fluctuations were measured using Brüel & Kjaer water-cooled microphones. Time varying heat release was recorded with two filtered fiber optic probes to detect OH radiation.

Control System

Schematic diagrams of the acoustic proportional control and fuel modulations control systems are given in Fig. 2a and b. The signals from the microphone sensors were fed into a signal-processing unit which delayed the input signal by a predetermined time and amplified it. The time-delayed signal was fed-back to drive the loudspeakers through an audio amplifier (Fig. 2a). For fuel modulation control, Fig. 2b, the driving signal had both DC and AC components that could be independently set. The signal from the microphone was amplified and band-pass filtered, 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.

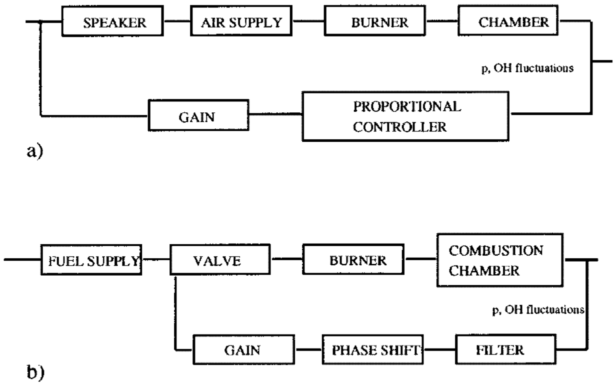

Fig. 2 Schematic diagrams of (a) acoustic proportional and (b) fuel modulation control systems

Visualization and Emissions Measurements

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 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 NO_2, combined in NO_x have been detected with a chemiluminescence analyzer. The detection of the remaining O_2 in the exhaust gas was based on the paramagnetic properties of oxygen in the analyzing device and was used to determine the equivalence ratio.

Results and Discussion

Structure of the instability

The results of previous investigations showed that several modes of thermoacoustic instability could be excited in the burner when it operates at a premixed mode by proper adjustment of the acoustic boundary conditions (Paschereit et al. 1998[15]). All the instability modes were related to combustion within large-scale structures that were excited in the combustion chamber due to interaction between various flow instabilities and the acoustic resonant modes of the combustor. The instabilities associated with the premixed mode of operation were at a normalized frequency $St = fD/U = 0.58$ and at $St = 1.16$, where f is the instability frequency, D the burner diameter and U the burner exit velocity. The $St = 0.58$ instability was the predominant mode. A typical level of the $St = 0.58$ instability was 29 dB above the background noise level. The instability at $St = 1.16$ was a helical mode while the mode at $St = 0.58$ was axisymmetric. The different instability modes were also visualized using a 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. The axisymmetric $St = 0.58$ instability is shown in Fig. 3 a, b, e, f at two phase angles of 0 and 180 degrees, in a premixed operation. The axisymmetric structure is demonstrated as well as the variable heat release during the cycle. The highest heat release, which is related to the OH intensity, was measured at a phase angle of 0 degrees, while the lowest level was measured at 180 degrees. A helical unstable mode was measured in premixed operation (Fig. 3 c, d, g, h). The high OH intensity shifted from the bottom shear layer for a phase-angle of 0 degrees to the upper shear layer at 180 degrees.

Flow Field

The flow exiting the swirl-generating burner was measured in a water tunnel facility. A negative mean velocity region near the burner axis showed the recirculation region, which provides one of the mechanisms for flame stabilization in this burner. The flow pattern near the axis is similar to wake flow behind a bluff-body. The flow instability associated with this region was therefore predominantly helical, resembling wake flow instability. Another region receptive to flow instabilities was the sudden expansion area at the burner exit plane. The flow at this area exhibited features of an annular jet. The jet formed two shear layers, the internal one with the recirculating flow downstream of the stagnation point in the inner backflow region, and the external one with the recirculation zone at the sudden expansion location. Cross-sectional profiles of the mean and turbulent velocity components

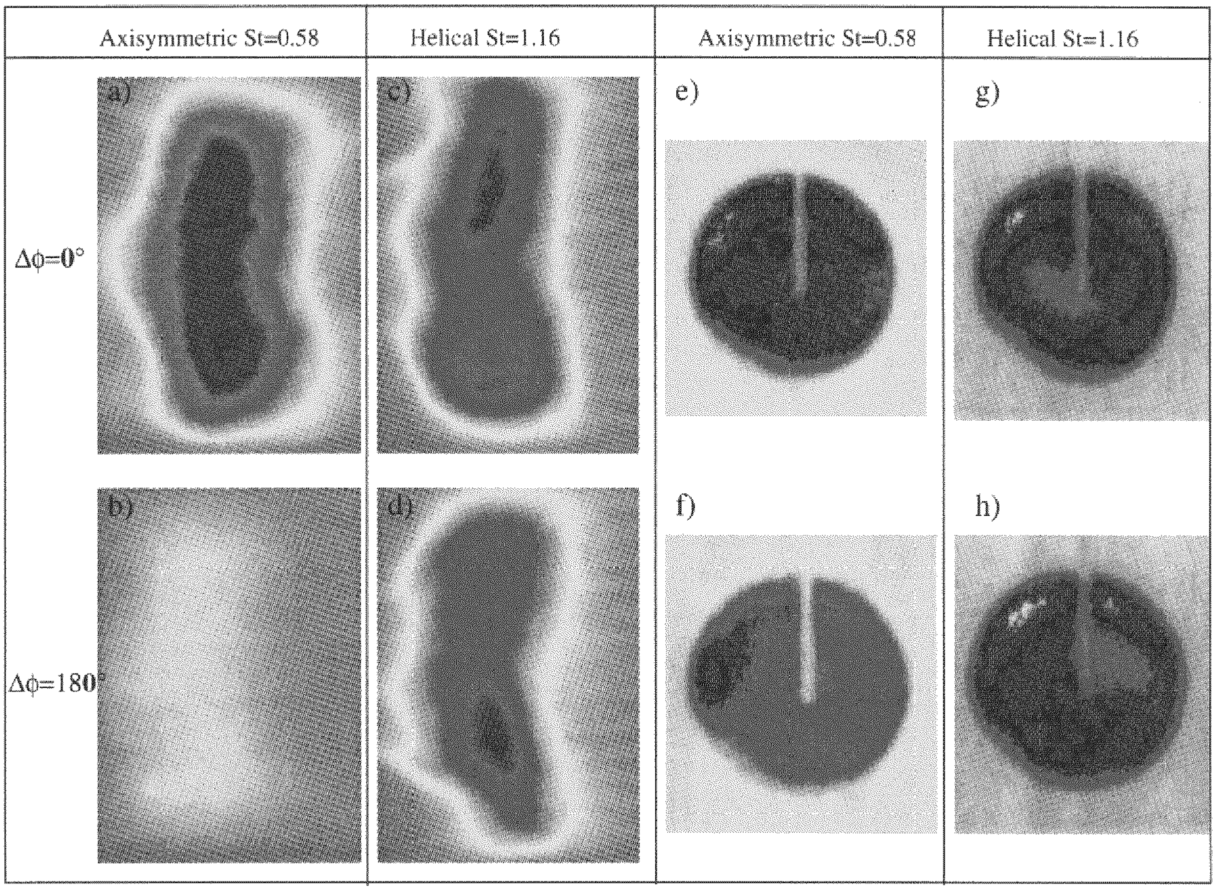

Fig. 3 Visualization of phase averaged OH-images at phase angles of 0 and 180 degrees. (a, b, e, f) Axisymmetric (premixed, $St = 0.58$). (c, d, g, h) Helical (premixed, $St = 1.16$).

are shown in Fig. 4. Only the inner wake region includes significant back flow. The main peak of the turbulent fluctuations was measured at the inflection point of the internal shear layer. The outer shear layer exhibits a small increase in turbulence level. One of the important flow features, which are significant to the thermoacoustic instability, is the dominant unstable mode in the shear layers. The inner shear layer exhibited primarily one fundamental unstable mode at a normalized frequency of $St = 1.2$ (Fig. 5). This mode could be related to the wake like profile of the inner recirculation zone and was of helical type. As shown in the combustion experiments, the outer shear layer was unstable to an axisymmetric mode at a normalized frequency of $St = 0.58$ (Fig. 6).

Combustion Control-Acoustic Actuators

A closed-loop proportional feedback control system was designed to reduce the coherence of the large-scale structures thus to suppress the level of pressure oscillations due to combustion instability. Speakers provided direct excitation of the shear layers in the combustor. The feedback loop consisted of a time delay-amplifier unit that fed the original microphone signal back to the speakers after a predetermined delay and amplification. The time delay or phase between the microphone signal and the speakers driving signal was varied between 0 and 360 degrees. The level of OH fluctuations in the shear layer at an axial distance of $x/D = 0.514$ was simultaneously recorded. The variation of the pressure and OH oscillations as a function of the relative phase between the microphone (sensor) and speakers (actuators) is shown in Fig. 7 for the axisymmetric unstable mode at $St = 0.58$. This controlled behavior is compared with the horizontal line depicting the pressure and OH fluctuations level when the controller is not operating. The amplification (gain setting) of the control signal was varied to study its effect on the reduction of pressure and OH oscillations at the optimal phase of 60 degrees. The results in Fig. 8 show that a minimum gain of 20 dB was necessary to reach maximum suppression of both the pressure and OH fluctuations. The figure also shows the destabilization of a secondary mode at $St = 0.92$ with increased

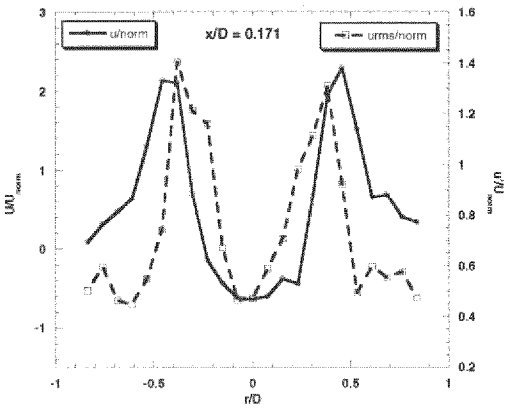

Fig. 4 Radial profiles of the axial mean and RMS velocity at $x/D = 0.171$.

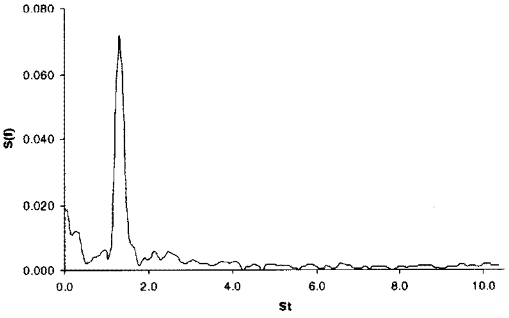

Fig. 5 Spectra of the axial velocity component in the inner shear layer.

gain.

Maximum suppression was obtained at a time delay corresponding to a phase difference of 60 degrees, while maximum destabilization of the combustion was observed at 270 degrees. At the optimal phase angle, the instability was suppressed by nearly 24 dB, while the maximum amplification was 2.9 dB. A phase-lock/phase shift (PLPS) controller achieved a maximum suppression of 5 dB for the same conditions (Paschereit et al. 1998[23]). The maximal suppression of the OH oscillations was obtained at 30-60 degrees. The OH fluctuations were reduced by over 25 dB indicating that the large-scale structures lost their coherence. The structure of the reacting vortices inside the combustor was assessed from radial cross-correlation measurement between two OH chemiluminescence filtered fiber-optic probes. To measure radial cross-correlation, one of the OH sensors was stationary in the upper shear layer at an axial distance $x/D = 0.514$ from the dump plane, monitoring the shear layer flow, while the other one was traversing the combustion zone radially at the same axial distance. The measurements were performed for two unstable

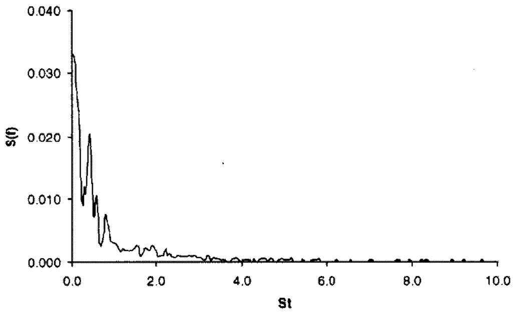

Fig. 6 Spectra of the axial velocity component in the outer shear layer.

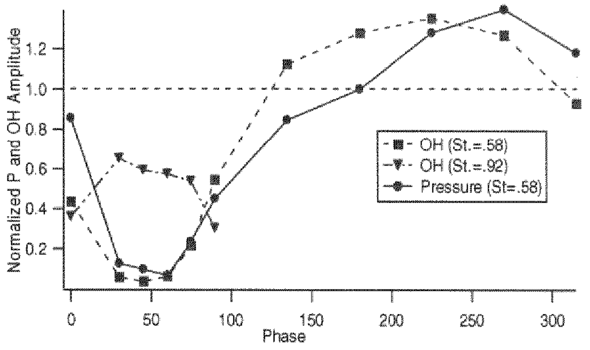

Fig. 7 Controlled pressure and OH oscillations for different phase shift angles.

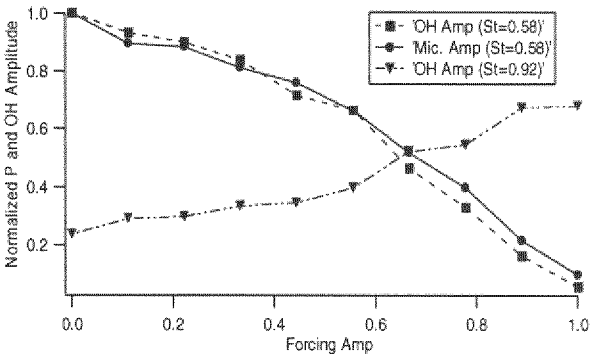

Fig. 8 Controlled pressure and OH oscillations for different forcing amplitudes.

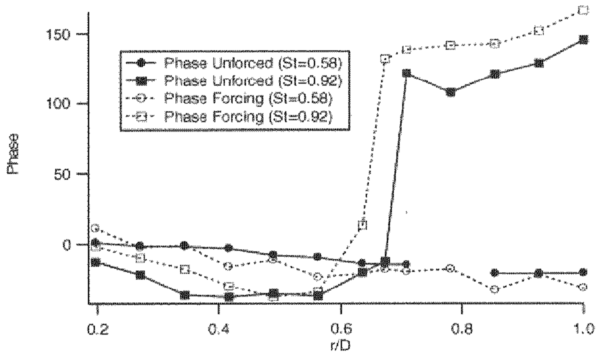

Fig. 9 Phase of radial OH correlations, without and with control.

Strouhal numbers, $St = 0.58$ (axisymmetric instability) and $St = 1.16$ (helical instability). The relative phase angles between the two OH signals are plotted as a function of $\Delta r/D$ in Fig. 9. The instabilities at $St = 1.16$ underwent a phase change of nearly 180 degrees corresponding to helical modes while the mode at $St = 0.58$ remained close to zero phase angle across the combustor, indicative of an axisymmetric mode. NO_x and CO emissions were monitored in the entire range of pressure oscillations control. The results, depicted in Figs. 10 and 11 show a 20% reduction of the NO_x and virtually no effect on CO levels, at the same time delay range that yielded pressure fluctuations stabilization. Nearly 10% increase in NO_x emissions was observed at 240 degrees. The concomitant NO_x emissions reduction and pressure oscillations suppression are both related to the reduced coherence of the vortical structures. Acoustic control caused uniform mixing, improved combustion without effect on CO production and evenly distributed temperature yielding low NO_x emission.

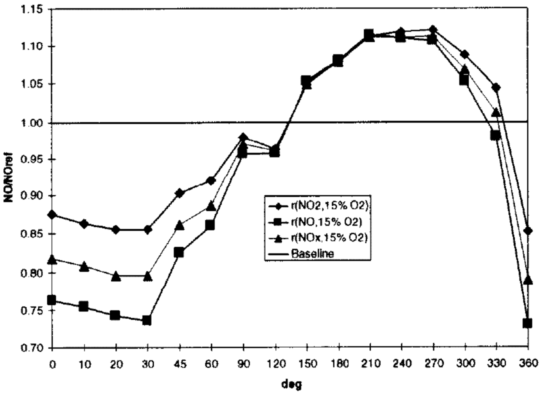

Fig. 10 NO_x emissions for various phase shifts in a closed-loop control system.

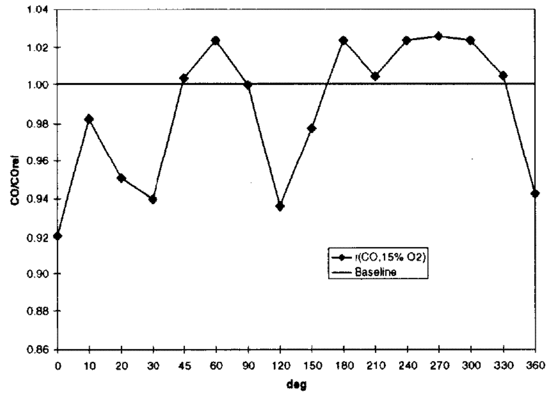

Fig. 11 CO emissions for various phase shifts in a closed-loop control system.

Combustion Control-Fuel Modulation Actuators

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 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. The pressure fluctuations were monitored using a microphone near the dump plane. OH radiation was measured at a distance of $x/D = 0.046$ from the burner exit in the shear layer.

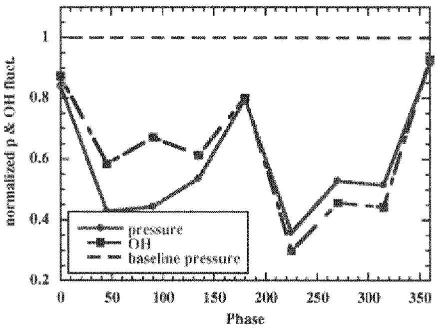

Fig. 12 Pressure and OH fluctuations suppression in a closed loop controller with antisymmetric pulsed fuel injection (amplitude $F/F_{max} = 50\%$).

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

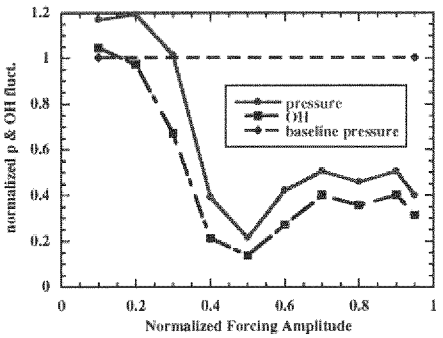

Fig. 13 Effect of amplitude variation on pressure and OH fluctuations suppression, antisymmetric fuel injection (phase=330 deg). Closed loop controller

symmetric fuel injection a level of pressure instability suppression of 12 dB was obtained at a fuel pulsation amplitude $F/F_{max} = 35\%$. The flame was near blow out at a certain range of phase angles.

Antisymmetric Fuel Pulsations

At a forcing amplitude of $F/F_{max} = 50\%$ the flame maintained stability in the entire range of phases (Fig. 12) 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. 13. At this forcing level, the NO_x emissions were substantially decreased (Fig. 14) as well as the CO emissions (Fig. 15).

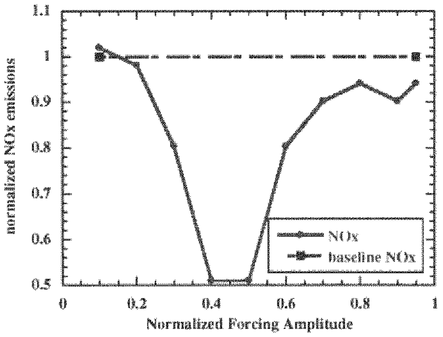

Fig. 14 NO_x emissions as a function of amplitude, antisymmetric pulsed fuel injection (phase=330 deg.). Closed loop controller.

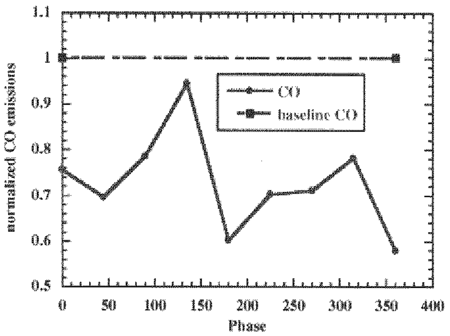

Fig. 15 CO emissions as a function of phase, antisymmetric pulsed fuel injection amplitude $F/F_{max} = 50\%$. Closed loop controller.

Open Loop Control by Pilot Flame Modulations

The axisymmetric instability mode (St=0.58) was stabilized by injecting secondary fuel to establish a pilot diffusion flame. The level of the pressure and OH fluctuations decreased with increased secondary fuel mass flow rate, until a minimum was reached for 4.4% pilot fuel addition (Fig. 16). At this point the axisymmetric instability was reduced by 20 dB.

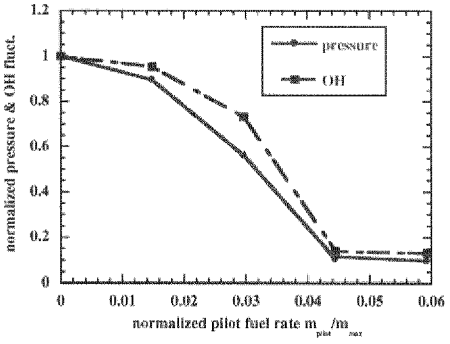

Fig. 16 Suppression of pressure and OH fluctuations by pilot fuel injection. Open loop controller.

It is usually undesirable to add diffusion flame to a premixed combustion due to potential increase in emissions. In the present case, NO_x emissions decreased while the secondary fuel addition was less than 3% and rapidly increased as the amount of secondary fuel exceeded this level (Fig. 17). Concurrently, the amount of CO decreased with increasing the secondary fuel indicating improved combustion efficiency (Fig. 17).

To minimize the amount of fuel injected in the pilot flame, pulsed injection at low frequencies was utilized. The low frequency pulsations were adjusted to be in the range commensurate with the time scales associated with the central recirculation zone. The pulsed injection also enabled modification of the duty-cycle to minimize the total amount of secondary fuel injected while maintaining sufficient heat release at each injection cycle.

The fuel flow rate was set at an intermediate level of 4.4% such that the increase in NO_x will not be excessive, and the duty-cycle was fixed at 20%. The

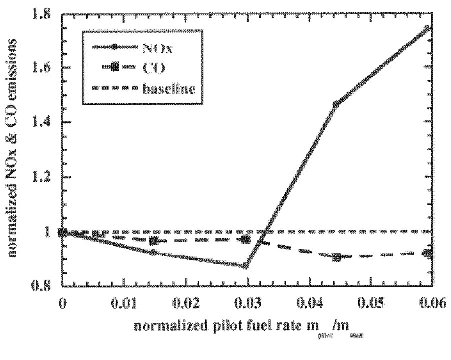

Fig. 17 NO_x and CO emissions as a function of pilot fuel injection. Open loop controller.

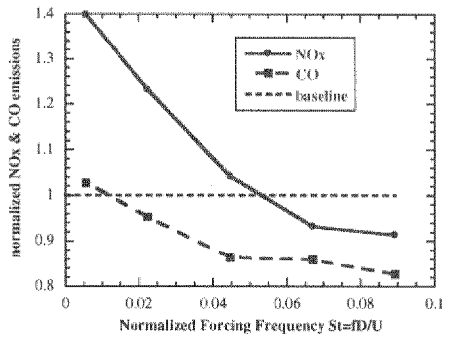

Fig. 19 Variation of NO_x and CO emissions with secondary fuel modulation frequency. Pilot fuel at 20% duty-cycle. Open loop controller.

pressure and OH fluctuation levels decreased monotonically with increasing normalized frequency (Strouhal number), until reaching a flat minimum level at $St = 0.065$, yielding a suppression level of over 20 dB (Fig. 18). The baseline level in this figure is the fluctuations level with continuous secondary fuel injection at the same flow rate. Emissions of NO_x increased at the lowest pulsation frequency, followed by a continuous decrease with increasing frequency until reaching a lower level than the reference conditions with continuous pilot fuel injection at $St > 0.055$ (Fig. 19). CO emissions exhibited similar behavior except that the CO level decreased below the baseline for $St > 0.01$.

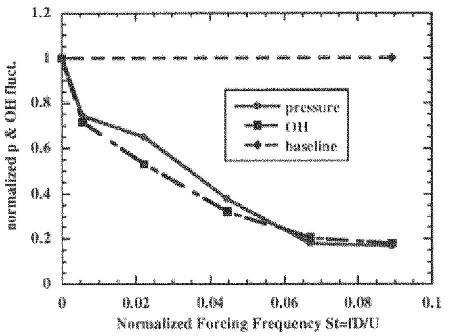

Fig. 18 Response of pressure and OH fluctuations to modulations of pilot flame. Pilot fuel at 20% duty-cycle. Open loop controller.

Conclusions

Active combustion control systems using proportional acoustic actuation and fuel modulations were applied to an experimental low-emission swirl stabilized combustor, in which the acoustic boundary conditions were modified to obtain unstable operation. Two unstable modes were investigated in fully premixed combustion: axisymmetric and helical. The unstable modes were associated with flow instabilities related to the recirculation region on the combustor axis and shear layer instabilities at the sudden expansion. The axisymmetric mode showed large variation of heat release during one period of oscillations, while the helical modes showed azimuthal variations of maximal heat release. Closed loop active control systems were employed to suppress the thermoacoustic pressure oscillations while maintaining low NO_x and CO emissions. Pressure sensors (microphones) monitored the combustion process and provided input to the control system. The signal of the microphone was delayed and amplified before being fed to the actuator. Acoustic actuation was utilized to modulate the airflow entering the swirl-generating burner. The acoustic excitation varied the mixing process between fuel and air and the combustion products. Suppression levels of up to 25 dB in the pressure oscillations and a concomitant 20% reduction of NO_x without affecting CO emissions were obtained using low acoustic power. Fuel or equivalence ratio modulations were used to control symmetric and helical unstable modes. Two methods were tested: symmetric and antisymmetric fuel injection. The tests showed that the antisymmetric modulations were more effective in suppressing 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. Antisymmetric fuel injection was effective in abating the symmetric mode instability providing that the modulation level was not excessive. Concomitant with pressure oscillation control, the emission levels of both NO_x and CO were reduced by up to 50 and 40%, respectively. The major effect of the control system was to reduce the coherence of the vortical structures that gave rise to the axisymmetric thermoacoustic instability. In addition to decoupling the combustion process from the flow instability, the temperature became uniform and NO_x forming high temperature zones within vortices were eliminated.

An open loop control system utilized by modulations of a secondary pilot flame. Control of low frequency symmetric instability was investigated. Adding a continuous flow of fuel into the pilot flame controlled the instability. However, modulating the fuel injection significantly decreased the amount of necessary fuel. The reduced secondary fuel resulted in a reduced power generation by the pilot flame and therefore yielded lower NO_x emissions. The pulsation frequency was chosen to match the time scales typical to the central flow recirculation zone that is used to stabilize the flame in the burner. Low frequency required longer duty-cycle, while at high frequency modulations a duty cycle of less than 10% was necessary. Suppression of pressure oscillations by up to 20 dB was recorded.

References

[1] Oster, D. and Wygnanski, I., "The forced mixing layer between parallel streams," *Journal of Fluid Mechanics*, Vol. **123**, 1982, pp. 91–130.

[2] Ho, C. and Huerre, P., "Perturbed free shear layers," *Ann. Rev. Fluid Mech.*, Vol. **16**, 1984, pp. 365–424.

[3] Crow, S. and Champagne, F., "Orderly structure in jet turbulence," *Journal of Fluid Mechanics*, Vol. **48**, 1971, pp. 567.

[4] Paschereit, C. O., Wygnanski, I., and Fiedler, H. E., "Experimental investigation of subharmonic resonance in an axisymmetric jet," *Journal of Fluid Mechanics*, Vol. **283**, 1995, pp. 365–407.

[5] Hasan, M. A. Z., "The Flow Over a Backward Facing Step under Controlled Perturbation: Laminar Separation," *Journal of Fluid Mechanics*, Vol. **238**, 1992, pp. 73–96.

[6] Paschereit, C. O., Schuermans, B., Polifke, W., and Mattson, O., "Measurement of transfer matrices and source terms of premixed flames," *ASME Turbo Expo '99*, Indianapolis, Indiana, USA, June 7-10 1999.

[7] Schuermans, B., Paschereit, C. O., and Polifke, W., "Modeling transfer matrices of premixed flames," *ASME Turbo Expo '99*, Indianapolis, Indiana, USA, June 7-10 1999.

[8] Schadow, K. C. and Gutmark, E., "Combustion instability related to vortex shedding in dump combustors and their passive control," *Progress of Energy and Combustion Science*, Vol. **8**, 1992, pp. 117–132.

[9] McManus, K. R., Poinsot, T., and Candel, S. M., "A review of active control of combustion instabilities," *Progress of Energy and Combustion Science*, Vol. **19**, 1993, pp. 1–29.

[10] Annaswamy, A. M. and Ghoniem, A. F., "Active Control in Combustion Systems," *IEEE Control Systems*, December 1995, pp. 49–63.

[11] Gutmark, E., Parr, T. P., Wilson, K. J., Hanson-Parr, D. M., and Schadow, K. C., "Use of Chemiluminescence and Neural Networks in Active Combustion Control," *Twenty third Symp. (Intl.) on Comb.*, The Comb. Inst., 1990, pp. 1101–1106.

[12] Schadow, K. C., Gutmark, E., and Wilson, K. J., "Active combustion control in a coaxial dump combustor," *Combustion, Science and Technology*, Vol. **81**, 1992, pp. 285–300.

[13] Sivasegaram, S. and Whitelaw, J. H., "The Influence of Swirl on Oscillations in Ducted Premixed Flames," *Combustion, Science and Technology*, Vol. **85**, 1991, pp. 195–205.

[14] Paschereit, C. O., Gutmark, E., and Weisenstein, W., "Role of Coherent Structures in Acoustic Combustion Control," *29th AIAA Fluid Dynamics Conference*, No. AIAA Paper 98-2433, Albuquerque, New Mexico, June 15-18 1998.

[15] Paschereit, C. O., Gutmark, E., and Weisenstein, W., "Flow-acoustic interactions as a driving mechanism for thermoacoustic instabilities," *4th AIAA/CEAS Aeroacoustics Conference*, No. AIAA paper 98-2274, Toulouse, France, June 2-4 1998.

[16] Paschereit, C. O., Gutmark, E., and Weisenstein, W., "Control of thermoacoustic instabilities and emissions in an industrial type gas-turbine combustor," *27th International Symposium on Combustion*, The Combustion Institute, August 2-7 1998.

[17] Paschereit, C. O., Gutmark, E., and Weisenstein, W., "Suppression of Combustion Instabilities by Acoustic Control of Shear Layer Properties," *Advances in Turbulence*, edited by U. Frisch, Kluwer Academic Publishers, Dordrecht/Boston/London, 1998, pp. 293–296.

[18] Paschereit, C. O., Gutmark, E., and Weisenstein, W., "Acoustic Control of Combustion Instabilities and Emissions in a Gas-Turbine Combustor," *Proceedings of the 1998 IEEE International Conference on Control Applications*, September 1-4 1998.

[19] Paschereit, C. O., Gutmark, E., and Weisenstein, W., "Suppression of Acoustically Excited Combustion Instability in Gas- Turbines," *5th AIAA/CEAS Aeroacoustics Conference*, Seattle, WA, USA, May 10-12 1999.

[20] Paschereit, C. O., Gutmark, E., and Weisenstein, W., "Coherent structures in swirling flows and their role in acoustic combustion control," *Physics of Fluids*, Vol. **9**, 1999, pp. 2667–2678.

[21] Paschereit, C. O., Gutmark, E., and Weisenstein, W., "Control of Thermoacoustic Instabilities in a Premixed Combustor by Fuel Modulation," *37th AIAA Aerospace Science Meeting and Exhibit*, No. AIAA Paper 99-0711, Reno, Nevada, January 11-14 1999.

[22] Paschereit, C. O., Gutmark, E., and Weisenstein, W., "Control of combustion driven oscillations by equivalence ratio modulations," *ASME Turbo Expo '99*, Indianapolis, Indiana, USA, June 7-10 1999.

[23] Paschereit, C. O., Gutmark, E., and Weisenstein, W., "Structure and Control of thermoacoustic instabilities in a gas-turbine combustor," *Combustion, Science and Technology*, Vol. **138**, 1998, pp. 213–232.