Conf-950629--3

DOE/METC/C-95/7179

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Conference Title:

1995 American Society of Mechanical Engineers Turbo Expo

Conference Location:

Houston, Texas

Conference Dates:

June 5 - 8, 1995

Conference Sponsor:

American Society of Mechanical Engineers

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ABSTRACT

A number of recent articles have demonstrated the use of active control to mitigate the effects of combustion instability in afterburner and dump combustor applications. In these applications, cyclic injection of small quantities of control fuel has been proposed to counteract the periodic heat release that contributes to undesired pressure oscillations. This same technique may also be useful to mitigate oscillations in gas turbine combustors, especially in test rig combustors characterized by acoustic modes that do not exist in the final engine configuration.

To address this issue, the present paper reports on active control of a subscale, atmospheric pressure nozzle/combustor arrangement. The fuel is natural gas. Cyclic injection of 14% control fuel in a premix fuel nozzle is shown to reduce oscillating pressure amplitude by a factor of 0.30 (i.e., -10 dB) at 300 Hz. Measurement of the oscillating heat release is also reported.

BACKGROUND

Reduction of combustion oscillations often presents a difficult challenge during turbine combustor development. Combustion oscillations are undesired because the resulting pressure oscillations can shorten component lifetime. Although a significant body of literature on combustion instability exists, practical solutions to instability problems are often clouded by uncertainties over the specific mechanisms driving a given oscillation. Prevention of instabilities during the design and development phase is further complicated because acoustic modes and operating conditions may be different between test rigs and final engine designs. Likewise, operation of a given combustor at new conditions, or with different fuel, may be accompanied by oscillating combustion.

Solution of combustion instability has typically required hardware modifications (i.e., passive control), or limiting the range of engine operation. Both of these solutions are costly, or unacceptable for certain cases. As an alternative, active control has been proposed as a different approach to eliminate combustion oscillations. Active control uses an external control device to mitigate the combustion instability. Active control attempts to limit the combustion oscillation by disrupting (in real time) the processes which create periodic heat release. Combustion which would otherwise oscillate is then stabilized by repeated adjustment of parameters affecting the combustion process. Many different control devices and strategies have been proposed in the last five years. Review articles by Candel (1992) and McManus et al. (1993) describe tests using sound input, periodic boundary layer disruption, spark discharge, and variable air flow as possible control techniques.

Among the various possible control techniques, periodic fuel injection seems to be a practical option for engine applications. The process is shown schematically in Figure 1. A turbine combustor is outfitted with an auxiliary fuel injector capable of adding a portion of the fuel in an unsteady manner. In principle, combustion oscillations could be negated by simply adding fuel out of phase with the established oscillation. Langhorne et al. (1990) were the first to attempt this type of control. Tests on a 0.25 MW afterburner rig showed that closed loop control, using the pressure signal to modulate just 3% of the total fuel input, could reduce the dominant pressure oscillation by 12 dB. Sivasegaram and Whitelaw (1992) tested a similar concept, again using periodic fuel injection to control the oscillation in an laboratory test rig. In their tests, the injected fuel flow was controlled in both open and closed loop configurations. Depending on the particular control approach, oscillating pressure amplitude was reduced by as much as 15 dB. A recent article by Schadow et al. (1992) reports on a number of control strategies, including fuel input modulation. Various levels of control were reported, depending on the specific situation. Finally, Schadow et al. (1993) compared fuel modulation to a slightly different strategy, using a spark discharge to burn a portion of the combustion fuel before entering the main combustion region of a dump combustor. Again, depending on the control conditions, a reduction in the peak pressure amplitude by as much 14 dB was achieved at one condition. Schadow et al. (1993) also reported the first test results at elevated pressure (1.9 atmosphere).

The above citations provide encouraging evidence that active control using pulsed fuel injection is a viable control technique for turbine combustor oscillations. Contemporary gas turbines have popularized the lean premixing fuel nozzle for pollutant control. Thus, this paper reports application of active control to a premixing fuel nozzle, using natural gas fuel. The approach is similar to the references mentioned above for afterburners and dump combustors. Fuel pulses are periodically injected into the fuel nozzle, and are shown to produce a significant reduction in oscillating amplitude.

EXPERIMENT DESCRIPTION

The experimental rig is shown in Figure 2. This atmospheric pressure rig consists of a 76 mm diameter refractory lined duct, with provision to mount premix fuel nozzles at the top of the duct. The duct geometry includes an extension leg which can be shortened (or lengthened) to support different acoustic modes. These modes can be readily calculated be treating the duct geometry as a classic acoustic branch (Kinsler et al., 1982). Calculating the impedance at the exhaust duct and setting the reactance to zero determines the resonant modes. At gas temperatures of 1475 K, this procedure predicts the following resonant frequencies (in Hertz) 87, 190, 300, 460, 600 Hz, and higher. As will be seen, the fuel nozzle preferentially excites the 300 Hz mode.

Unsteady pressure was measured using a piezoelectric pressure transducer mounted at the bottom of the extension leg of the combustor duct. Time varying heat release was recorded with a fiber-optic OH emission probe mounted near the exit of the nozzle. The probe is a 1.6 mm diameter sapphire rod, connected with a fiber optic cable to an optical filter and photomultiplier tube. The filter is centered at 310 nm, (10 nm bandwidth) and will detect emission from excited OH radicals which exist momentarily during the combustion reaction. As described by Keller and Siato (1987), the excited state OH emission is approximately proportional to the rate of combustion in the region viewed by the probe. The sapphire rod accepts radiant emissions from a conic region with a 15 degree viewing angle, extending from the probe tip. The probe was mounted at a slight angle from the duct axis, viewing through the combustion zone. Thus, the OH measurement is a line of sight measure of the heat release through the portion the flame within the probe viewing angle.

Also shown on Figure 2, thermocouples designated 'A' and 'B' record the gas temperature (approximately) at the duct centerline, 6.3 cm and 47 cm downstream of the fuel nozzle.

A detailed sketch of the fuel nozzle used in these experiments is shown in Figure 3. A central 12.7 mm stainless steel tube is used to supply pre-mixed fuel and air to the pilot flame on the nozzle axis. The pilot air flow rate was 0.56 g/s with the pilot fuel set to establish the peak flame temperature on thermocouple 'A' (i.e., stoichiometric). It is mentioned that subsequent testing has shown that both the oscillating behavior and control effects are sensitive to the quantity of pilot fuel flow; this is discussed later. The pilot flame is lit with an internal spark electrode approximately 75 mm upstream of the nozzle exit. The pilot tube is surrounded by the premixing annulus. Natural gas and air are mixed in the annulus upstream of a wire mesh flow straightener. The premixed fuel and air pass through straight-finned swirl vanes, angled 45 degrees from the nozzle axis. For the results described here, premix fuel and air flow rates are 0.4 g/s and 9.9 g/s respectively, corresponding to a heat input of approximately 20 kW.

A bypass route for the premix fuel is provided as shown on Figure 2. The bypass valve was adjusted to send a small portion of the premix fuel to the bypass port, to induce oscillating combustion; see the discussion below. The total flow rate of premix fuel is unchanged by opening this bypass. The natural gas fuel injector, used for control, is connected through the control port, located across the diameter of the nozzle from the bypass port. The fuel injector is a commercial automotive fuel injector, used for natural gas powered automobiles. The length of tubing between the bypass valve and the fuel nozzle was 37.5 cm. Likewise, the tubing length between the fuel injector solenoid and the nozzle was also 37.5 cm. These lengths are critical, because acoustic resonance in the tubes contribute to the combustion oscillation, described later.

RESULTS

The nozzle shown in Figure 3 was initially tested with the control fuel injector turned off, and the bypass valve closed. In this configuration, the nozzle produced essentially steady combustion. In contrast to this stable operation, a significant instability was readily established when approximately 15% of the premix fuel was sent to the bypass port. Figure 4 shows the pressure and OH signal corresponding to this bypass condition. A 4.5 kPa RMS pressure signal is established at 300 Hz. Figure 5 shows an ensemble average of one cycle of the pressure and heat release oscillation. Notice that the pressure has an initial inflection point followed by a further increase in amplitude, while the OH curve has no corresponding inflection point. The "double-peaks" appearing in the pressure curve are believed to result from the phase difference between the heat release and acoustics. Because the pressure transducer was not located at the point where combustion occurs, the exact phase relation between pressure and heat release cannot be inferred from Figure 5.

The exact mechanism driving this oscillation is only briefly discussed here. Given the magnitude of the pressure fluctuations inside the combustor, significant pressure and velocity variations are expected inside the premixing annulus. The acoustic response of the gas in the bypass tube produces a periodic variation in the bypass fuel flow. The resulting oscillation in the premix fuel/air ratio causes a variation in heat release which drives the pressure oscillation. This fuel/air variation has been well-documented in rocket oscillations (Harrje and Reardon, 1972), and in some gas turbine combustors (Kenworthy et al., 1989). Experimental and theoretical work in progress is aimed at developing a detailed description of the oscillation mechanism in this nozzle.

Active control of the oscillation was attempted by adding 0.067 g/s of natural gas control fuel through the pulse injector. This represents 14% of the total flow rate of fuel, and produces an overall equivalence ratio of 0.85. The control fuel injector was operated with a frequency of 50 Hz, and a pulse width of 16 ms. The resulting pressure oscillation in the combustor duct is shown in Figure 6. Notice the injector open duration is shown on this plot by thick lines above the pressure signal. The duration was relatively long compared to the pressure cycle. The added control fuel contributes to the oscillation in the same manner as the by-pass fuel. Comparing Figures 4 and 6, the added control fuel produced an even larger oscillation. Again, the only difference between these two figures was the addition of control fuel at 50 Hz, with a long pulse duration. Notice in Figure 6 that the heat release (OH) spectra does not show any appreciable signal at the fuel injector driving frequency (50 Hz). This confirms that the long pulse width is essentially equivalent to steady fuel input.

Without changing any other operating conditions, the effect of shorter pulse width (7.2 ms) is shown in Figure 7. Comparing to the previous figure, and Figure 4, the oscillation has been noticeably reduced. Statistical analysis of the waveforms shows that the RMS pressure amplitude was reduced by a factor of 0.30 from the uncontrolled case (Figure 4). Referring to the OH spectra, the control frequency of 50 Hz is evident, indicating the control fuel injection is indeed causing a variation in heat release at the control frequency.

Tests were conducted over a range of pulse widths. Figure 8 shows the RMS pressure level as a function of the pulse width, at the driving frequency of 50 Hz. The pulse width is expressed as a percent of the fuel injector period at 50 Hz. The oscillation is seen to drop off dramatically at a pulse width of less than 35%; this is comparable to three periods of the 300 Hz oscillation. Variation in the pulse width was tested several times to determine the pulse width required for effective control. In practice, a precise value could not be determined; there is some latitude in where the control takes effect. Further tests were conducted at a fixed pulse width, but with a driving frequency between 50 and 80 Hz. The driving frequency had little effect on control until reaching 80 Hz, where the large amplitude pressure oscillations resumed. Tests in progress will map out the required combination of pulse width and frequency needed for control.

Before concluding, it is mentioned that ongoing tests have shown that both the baseline oscillation, and the control behavior are remarkably sensitive to a number of geometric and operating parameters. For example, lowering the pilot tube into the combustion region by as little as 3 mm could negate the baseline oscillation. Changing the pilot fuel flow by just a few percent or changes in the temperature of the refractory combustor duct could likewise negate (or promote) either the oscillation or the control effect. While the control behavior described here could be qualitatively established by carefully setting flow rates, the quantitative level of the control achieved was affected by apparently minor changes in nozzle geometry (i.e., orientation of the swirl vanes, precise location of the pilot tube, etc.). This sensitivity may be an inherent feature of swirl stabilized flames. In a nozzle similar to the one studied here, Starner and Bilger (1986) report that even a 0.2 degree misalignment of the central fuel tube can produce significant asymmetries in observed (diffusion) flame structure. Milosavljevic et al. (1990) showed that a swirl nozzle with a central fuel tube can produce both symmetric and asymmetric flame structures, depending on the flow rates. For the present investigation, it is suggested that the (delicate) orientation of flame asymmetries with respect to the bypass or control ports may play a role determining the magnitude of the oscillating or controlled response; this issue is under investigation.

SUMMARY AND CONCLUSIONS

A 20 kW atmospheric pressure natural gas combustor has been used to study the active control of combustion oscillations. Combustion oscillations arising from fuel/air variations in a premixing fuel nozzle are controlled by periodic injection of fuel in the premixing zone of the fuel nozzle. Specifically, a 300 Hz oscillation with 4.5 kPa RMS pressure amplitude was reduced by a factor of 0.30 (-10 dB). Control was accomplished using 50 Hz open-loop injection of 14% of the total fuel. In addition to recording the transient pressure signal, transient heat release was measured using a fiber-optic flame emission probe. Heat release measurements show that short duration fuel pulses produce a corresponding variation in the heat release, at the control frequency. Work in progress is aimed at identifying the specific parameters required for successful control, and understanding the observed sensitivity to various operating and geometric parameters.

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FIGURES

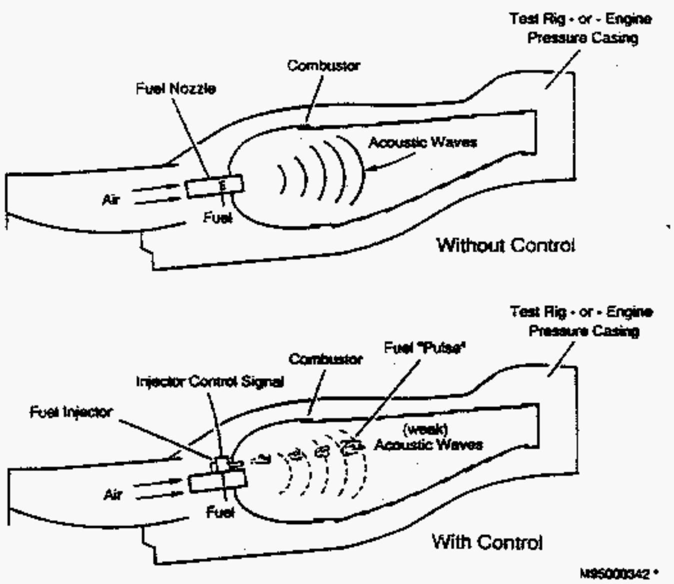

FIG. 1. SCHEMATIC OF ACTIVE CONTROL PROCESS USING PERIODIC FUEL INJECTION.

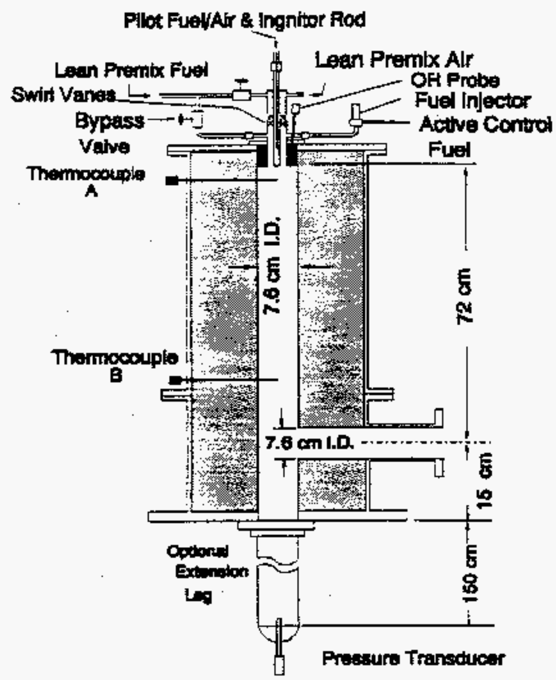

FIG. 2. EXPERIMENTAL CONFIGURATION.

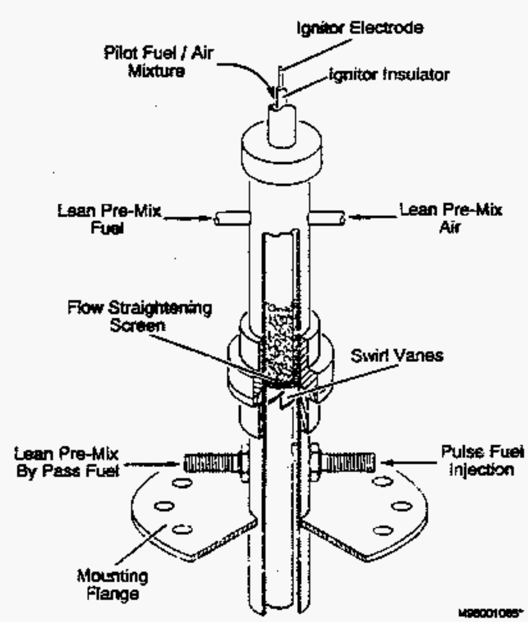

FIG. 3. DETAILED VIEW OF THE PREMIX FUEL NOZZLE.

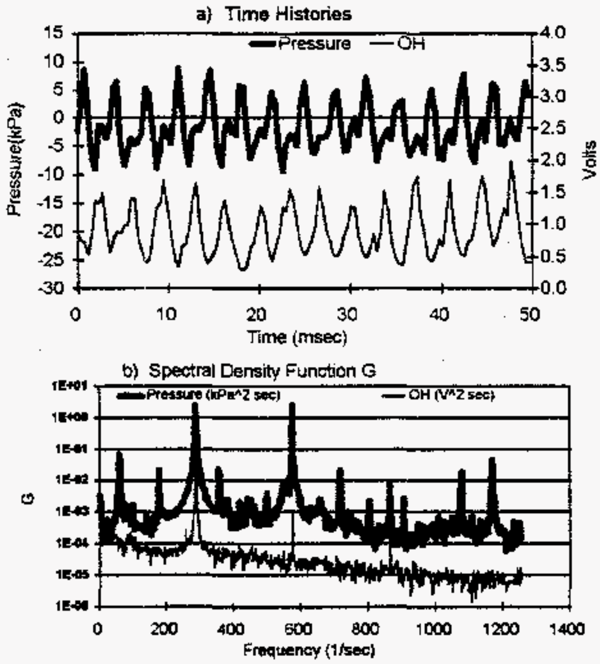

FIG. 4. TIME HISTORIES AND SPECTRA OF PRESSURE AND OH (HEAT RELEASE) SIGNALS WITH NO CONTROL FUEL.

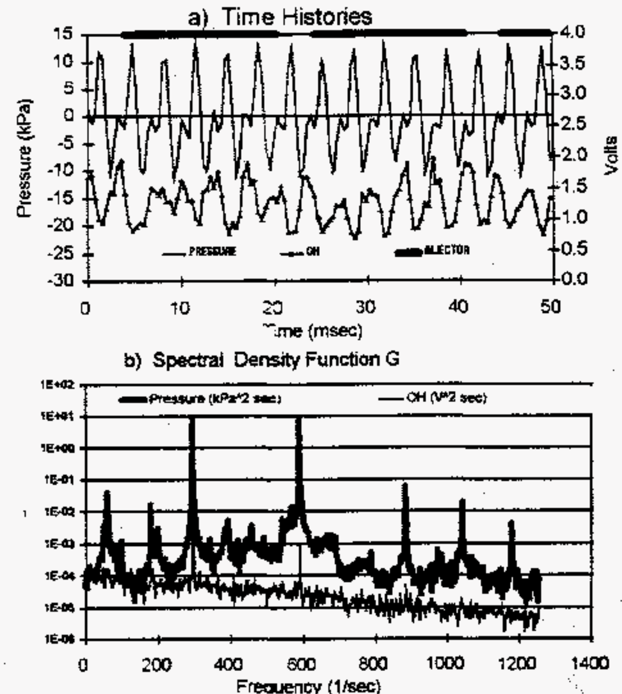

FIG. 6. TIME HISTORIES AND SPECTRA OF THE PRESSURE AND OH SIGNALS WITH 0.067 G/S CONTROL FUEL, 50HZ. (THICK LINES IN (a) INDICATE PULSE WIDTH.)

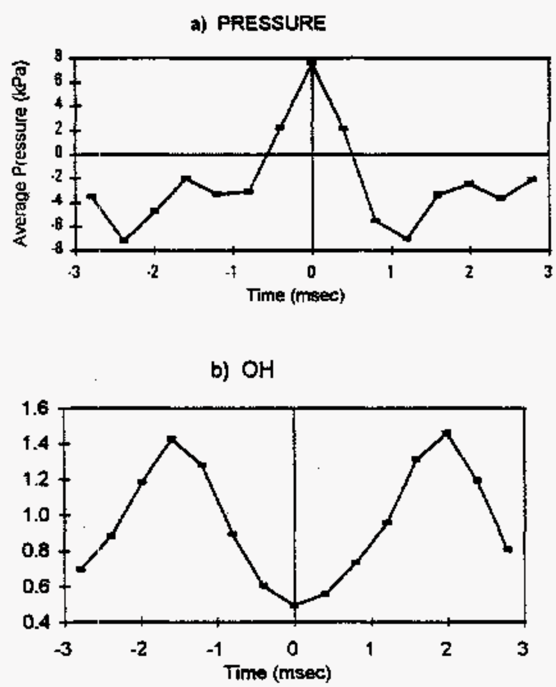

FIG. 5. ENSAMBLE AVERAGE OF A SINGLE CYCLE OF THE SIGNAL SHOWN IN FIG. 4.

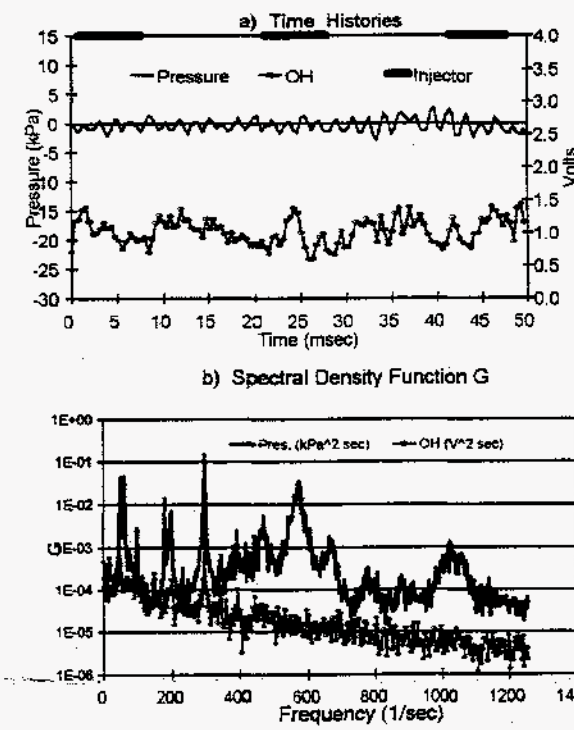

FIG. 7. TIME HISTORIES AND SPECTRA WITH NARROW PULSE WIDTH AT CONDITIONS COMPARABLE TO FIG. 6.

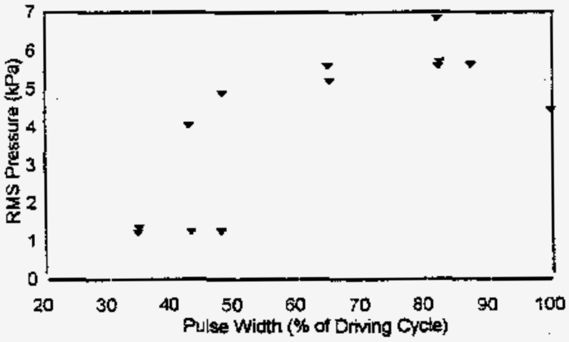

FIG. 8. EFFECT OF PULSE WIDTH ON COMBUSTOR DYNAMIC PRESSURE.