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Oscillating Combustion from a Premix Fuel Nozzle

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INTRODUCTION

Stringent emissions requirements for stationary gas turbines have produced new challenges in combustor design. In the past, very low NOx pollutant emissions have been achieved through various combustion modifications, such as steam or water injection, or post-combustion cleanup methods such as selective catalytic reduction (SCR). An emerging approach to NOx abatement is lean premix combustion. Lean premix combustion avoids the cost and operational problems associated with other NOx control methods. By premixing fuel and air at very low equivalence ratios, the high temperatures which produce NOx are avoided.

The challenges of premix combustion include avoiding flashback, and ensuring adequate fuel/air premixing. In addition, the combustion must be stable. The combustor should not operate so close to extinction that a momentary upset will extinguish the flame (static stability), and the flame should not oscillate (dynamic stability). Oscillations are undesirable because the associated pressure fluctuations can shorten component lifetime (Cutrone, et. al 1985). Unfortunately, experience has shown that premix fuel nozzles burning natural gas are susceptible to oscillations. Eliminating these oscillations can be a costly and time consuming part of new engine development. As part of the U.S. Department of Energy's Advanced Turbine Systems Program (Report to Congress, 1994), the Morgantown Energy Technology Center (METC) is investigating the issue of combustion oscillations produced by lean premix fuel nozzles.

A considerable body of literature on combustion oscillations is available. Rocket motor oscillations were extensively studied in the 1960's and 1970's, providing much information on instability mechanisms in rocket applications (Harrje and Reardon, 1972). Combustion oscillations in propulsion systems such as afterburners and dump combustors continue to receive research attention, with both passive and active control schemes considered for oscillation mitigation (Candel, 1992).

There are two major distinctions between these applications, and gas turbine premix fuel nozzles. First, most premix fuel nozzles use swirl stabilization; afterburners are usually unswirled. Second, in gas turbines, the intent is to operate the nozzle as lean as possible; a pilot flame may even be used to stabilize very lean combustion. Again, such an approach is atypical for afterburner or dump combustor applications.

To address these distinctives, METC is evaluating various techniques to stabilize oscillating combustion in gas turbines. Tests results from a premix fuel nozzle using swirl stabilization and a pilot flame are reported here. Data suggest that two mechanisms are involved in driving the oscillations. The first mechanism has been well-documented in other burners: acoustic feedback between the combustor and nozzle fuel/air supply produces variations in fuel/air ratio. A second mechanism appears to involve the transport of swirling flow from the nozzle swirl vanes to the combustor interior.

EXPERIMENTAL DESCRIPTION

The experiment is shown in figure 1. Combustion occurs at the top of a 76mm diameter refractory lined duct. A premix fuel nozzle is mounted at the top of the duct, and the duct acoustics can be modified by changing the length of the optional extension leg at the bottom. A detailed view of the premix fuel nozzle is shown in figure 2. A central 12.7 mm stainless steel tube is used to supply premixed fuel and air to the pilot flame on the nozzle axis; this pilot flame is usually set at stoichiometric with 0.56 g/s of air flow. The swirl vanes were machined from solid stainless steel bar-stock, producing straight fins, angled at 45 degrees from the nozzle axis. The fins fit snugly inside the 2.54 cm pipe that forms the outer nozzle annulus. A bypass route for the lean premix fuel is provided as shown on figure 1, and attaches to the premix annulus at a port located *below* the swirl vanes, see figure 2. The bypass fuel serves to inject a portion of the lean premix fuel downstream of the swirl vanes, producing the oscillation described next.

OSCILLATIONS FROM THE BYPASS FUEL

The bypass flow was introduced to excite oscillations which could then be studied in subsequent control tests (Richards et al. 1995). Oscillations were typically achieved using less than 10% of the total lean premix fuel in the bypass. The bypass tube responds to acoustic excitation in the combustor/fuel nozzle, and produces a variation in the fuel flow which can drive oscillations. This type of oscillation has been documented in liquid rockets (Harrje and Reardon, 1972), some gas turbine (Kenworthy et al., 1989), and in many industrial burners (Putnam, 1971). The conditions which drive oscillations can be identified by considering the resonant frequencies inside the combustion chamber, and then evaluating the fuel flow response at those frequencies. A schematic of processes inside the fuel nozzle is shown in figure 3.

Following an approach similar to Putnam (1971), we represent the *fluctuating* component of the bypass fuel in complex notation as $\dot{m}_b$ and we assume that the (complex) fluctuating pressure p at the bypass port is in-phase with the combustor pressure. This is acceptable for the relatively short nozzles used in gas turbines. We can calculate $\dot{m}_b$ from the pressure p and the bypass tube acoustic impedance Z (at x=0) as follows: Note that $\dot{m}_b$ is the product of the fuel density, tube cross section area (A_{tube}) and fluctuating velocity (-u); the coordinate system requires a negative sign on the velocity to indicate increasing mass flow. Then,

$$\dot{m}_b = -\rho \frac{p}{Z} A_{tube}^2 \quad \text{where} \quad Z = \frac{p}{u} A_{tube} \tag{1}$$

Next, we can determine the fuel mass fluctuation arriving at the flame front ($\dot{m}_c$) by noting that the (mean) nozzle flow carries the fuel to the flame front after a transport time (t_t) which is simply the distance from the bypass port to the flame, divided by the mean axial flow velocity:

$$\dot{m}_c = e^{-j\omega t_t}\,\dot{m}_b = \rho\, A_{tube}^2\, p \left[-\frac{e^{-j\omega t_t}}{Z} \right] \tag{2}$$

If we assume that the fuel burns immediately when it arrives at the flame front (which is reasonable for premixed combustion), the heat release is proportional to $\dot{m}_c$. To satisfy Rayleigh's criterion, maximum heat release should occur with maximum pressure. Thus, equation (2) suggests a criterion for oscillations: the phase angle of the term in brackets should be an integer multiple of 2π to align the heat release and acoustic pressure:

$$\text{Phase angle} \left\{ -\frac{e^{-j\omega t_t}}{Z} \right\} = 2\pi,\ 4\pi,\ 6\pi,\ \ldots \tag{3}$$

We point out that equation (3) is valid for a general impedance value Z. This equation could be useful to evaluate the stability of commercial fuel nozzles where the impedance of the fuel injection ports has been measured. In the present case, the fuel injection port is simply a tube, so we calculate the impedance from standard relations for a tube acoustically closed at one end (Kinsler et al., 1982). For the geometry and conditions studied here, the result is:

$$\frac{t_t}{t_a} = 0.75,\ 1.75,\ 2.75\ \ldots \tag{4}$$

In this equation, t_a is the period of the acoustic cycle, i.e.; the reciprocal of the oscillating frequency. Equation (4) is now compared to laboratory observations. The fuel nozzle described earlier was tested over a range of air flow rates from 9 to 18 g/s, at various equivalence ratios, The transport time in (4) was calculated using the advection time from the bypass port to the end of the nozzle, based on the mean flow velocity. This approach does not account for the (short) distance between the end of the fuel nozzle and the flame front.

Figure 4 shows the RMS pressures observed experimentally with bypass flow present. The abscissa is the ratio of transport time and acoustic period at the observed oscillating frequency. Oscillations are centered around 0.8, close to the first value predicted by equation (4). Tests in progress are aimed at expanding the database to cover additional conditions and further confirm equation (4).

These oscillations appear to be consistent with the classic fuel-feed mechanism described by Putnam (1971) and many others. A brief, additional confirmation of equation (3) was tested by simply choking the bypass tube at the premix nozzle annulus, creating an infinite impedance (Z) in equation (3). Limited testing showed that bypass induced oscillations did not occur, thereby confirming the role of the bypass tube response in driving oscillations.

OSCILLATIONS WITHOUT BYPASS FUEL

The preceding results confirm that oscillations described by classic fuel (or air) feed fluctuations can be observed in lean premix fuel nozzles, and can be described by simple time-lag theories for combustion instability. However, during the course of testing, we observed several oscillations without the bypass fuel flow. Because the main lean-premix flows were choked at the top of the nozzle, we did not attribute these oscillations to fuel (or air) fluctuations. For reasons explained below, these data are plotted in figure 5 using a graph similar to figure 4, except the transport time is based on advection time from the swirl vanes to the end of the nozzle. The data cover a range of equivalence ratios and frequencies from 303 to 430 Hz (altered by changing the combustor extension, figure 2).

We note that oscillations are essentially absent until the time ratio drops below 1.5, where oscillations are immediately observed. This behavior again suggests that the instability may be described by a simple time lag theory. Here, the transport time lag is based on the advection time from the swirl vanes to the end of the nozzle. If the time lag concept is correct, it raises the question: what is transported from the vanes to the nozzle exit?

When oscillations occur, the pressure amplitude is sufficient to produce significant variations in axial velocity within the nozzle annulus. Numeric modelling of the fuel nozzle during oscillating combustion has shown that axial velocities can vary by more than 20% during oscillating combustion (depending, of course, on the magnitude of the dynamic pressure). The fixed geometry swirl vanes will then produce a corresponding variation in tangential velocity. Thus, the annular nozzle flow is characterized by regions of high and low tangential velocity, convected along with the main axial flow. These variations in tangential velocity are proposed to alter the heat release rate as they arrive at the nozzle exit.

Exactly how the fluctuations in tangential velocity would modify the heat release rate is unclear without a detailed picture of events occurring at the flame front. The time ratio data (figure 5) suggest that a time of less than 1.5 acoustic cycles is needed for oscillations. With a time ratio of 1.5, fluid moving through the swirl vanes will arrive at the nozzle exit 1.5 acoustic cycles later. Thus, during the low acoustic pressure, high axial (and tangential) velocities pass from the swirl vanes and arrive at the flame front 1.5 acoustic cycles later - at the peak of the acoustic pressure. To satisfy Rayleigh's criterion, the arrival of these higher tangential velocities must serve to align the phase between increased heat release, and the acoustic pressure. Higher tangential velocities would then need to accelerate the heat release rate, via enhanced mixing, changes in the flame structure, recirculation strength, or some other mechanism.

The proposed behavior is tentative. A wider range of flow rates would provide further confirmation that oscillations occur as described. The limited data below time ratio 1.0 appear to suggest a reduction in the RMS pressure, as would be expected for a time lag mechanism, but more data is needed at these conditions to confirm this behavior. Additional data for time ratios below 0.5 should again produce an increase in RMS pressure by aligning the arrival of higher tangential velocities with the high acoustic pressure. Tests using a shorter fuel nozzle will be used to confirm this expectation.

In closing, we mention that some tests have been conducted on a fuel nozzle of similar geometry, but with the distance from the swirl vanes to the nozzle exit increased by a factor of 1.9; there were no other changes to the nozzle geometry. Oscillations were again observed for a time ratios between 1.2 and 1.5, consistent with the mechanism described above.

SUMMARY

A lean premix fuel nozzle, burning natural gas, is being studied to identify methods to prevent combustion instability in stationary gas turbines. The nozzle geometry is typical of premix gas turbine nozzles, using swirl vanes and a central pilot flame to anchor the premixed combustion. Oscillations were deliberately induced by directing a portion of the fuel to a port below the swirl vanes. The resulting oscillations are consistent with existing theories for combustion instability. A second type of oscillation was also observed; data suggest that this oscillation is related to variations in the tangential velocity being convected from the swirl vanes to the end of the nozzle. Tests in progress are aimed at confirming the proposed behavior.

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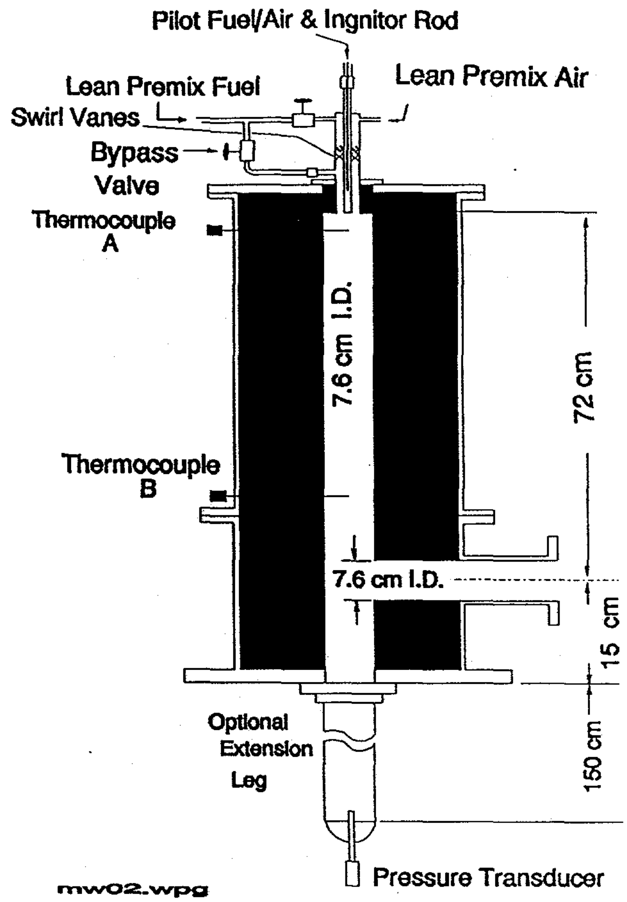

Figure 1. Experimental configuration.

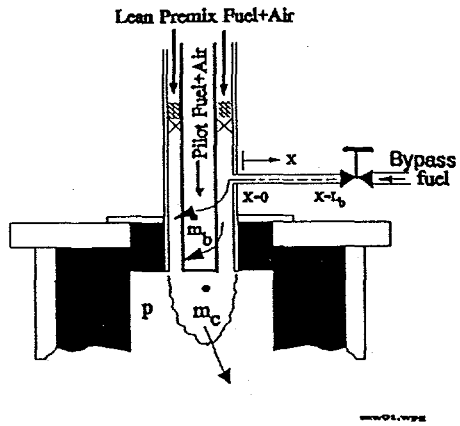

Figure 3. Schematic of processes inside the nozzle during oscillations.

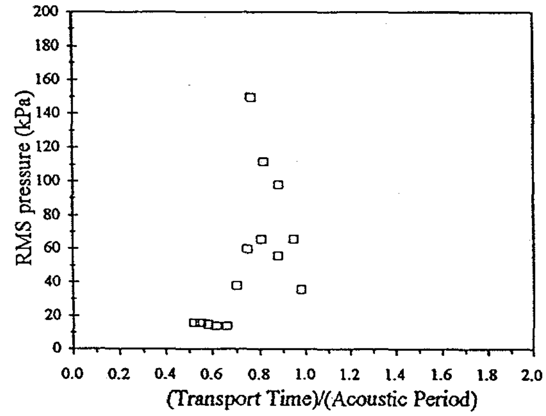

Figure 4. RMS pressure as a function of the time ratio and with bypass fuel.

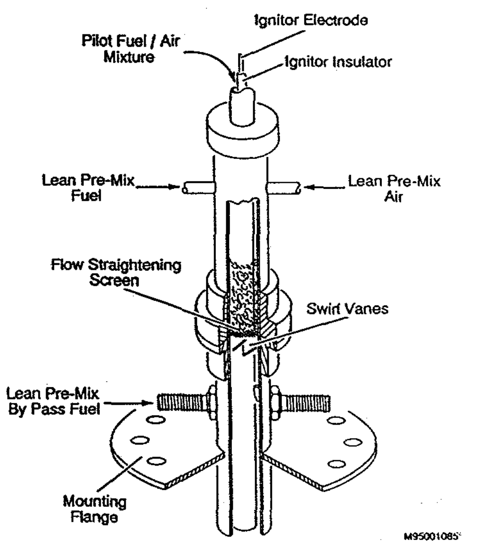

Figure 2. Close-up view of nozzle.

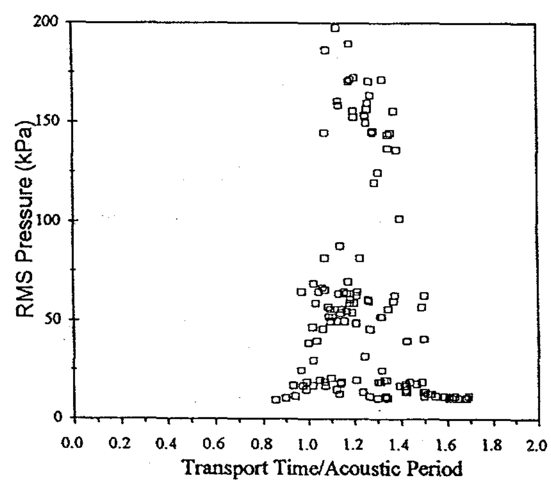

Figure 5. RMS pressure as a function of the time ratio without bypass fuel.