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Design Factors for Stable Lean Premix Combustion

Authors:
G. Richards
M. Yip
R. Gemmen

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5.1 Design Factors for Stable Lean Premix Combustion

George A. Richards (GRICHA@metc.doe.gov; 304-285-4458)
M. Joseph Yip (MJYIP@metc.doe.gov; 304-285-5434)
Randall S. Gemmen (RGEMME@metc.doe.gov; 304-285-4536)
Morgantown Energy Technology Center

Introduction

The Advanced Turbine Systems (ATS) program includes the development of low-emission combustors. Low emissions have already been achieved by premixing fuel and air to avoid the hot gas pockets produced by nozzles without premixing. While the advantages of premixed combustion have been widely recognized, turbine developers using premixed nozzles have experienced repeated problems with combustion oscillations. Left uncontrolled, these oscillations can lead to pressure fluctuations capable of damaging engine hardware. Elimination of such oscillations is often difficult and time consuming — particularly when oscillations are discovered in the last stages of engine development.

To address this issue, METC is studying oscillating combustion from lean premixing fuel nozzles. These tests are providing generic information on the mechanisms that contribute to oscillating behavior in gas turbines. METC is also investigating the use of so-called "active" control of combustion oscillations. This technique periodically injects fuel pulses into the combustor to disrupt the oscillating behavior. Recent results on active combustion control are presented in Gemmen et al. (1995) and Richards et al. (1995). This paper describes the status of METC efforts to avoid oscillations through simple design changes.

Approach

METC uses two experimental devices to study combustion oscillations. An atmospheric-pressure combustion duct (Figure 1) is used to study combustion oscillations produced by a premixing fuel nozzle. This combustor is used to screen various concepts for stable combustion, including changes to nozzle geometry and active control. Operation at atmospheric pressure allows relatively quick assessment of performance without the complications of pressurized operation. The fuel nozzle is mounted at the top of a 76-mm (3-in) refractory-lined duct. The fuel nozzle geometry is typical of current combustor designs, using swirl-vanes to generate a recirculation zone downstream of the nozzle exit. The 25-mm (1-in) annular swirl flow surrounds a 12.7-mm (0.5-in) pilot tube, which produces a pilot flame on the nozzle axis. The pilot flame is independent of the main lean premix flow exiting the nozzle annulus. The pilot allows flame-anchoring at conditions that would otherwise be too lean to support stable combustion. An optional extension leg at the bottom of the combustion duct allows changes to the acoustic frequencies that characterize the combustor. Tests results from this combustor are described below.

To complement tests conducted at one atmosphere pressure, METC uses a gas turbine

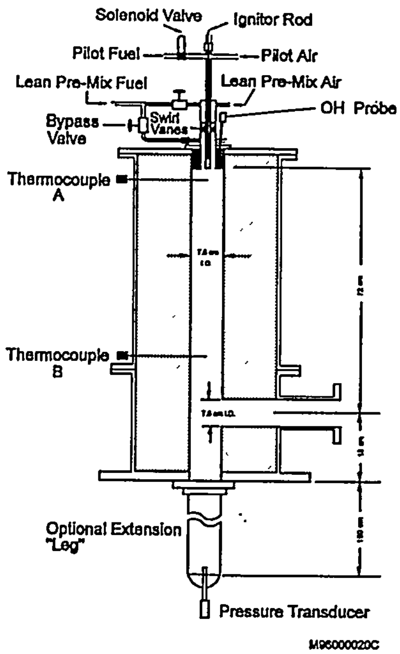

Figure 1. METC Atmospheric Pressure Combustor

style combustor (Figure 2). The combustion chamber is a water-cooled, cylindrical liner that has a diameter of 20 cm (7.9 in). To produce various acoustic modes, the liner is fitted with a removable refractory plug that is mounted on a seal ring as shown. The refractory is cast with a 7.5-cm (3.0-in) diameter passage on the central axis to form a cylindrical exhaust nozzle for the combustion region. The combination of the combustion chamber and the exhaust nozzle define a Helmholtz resonator with frequencies of interest to the gas-turbine designer (several hundred Hertz). The frequency can be adjusted by changing the dimension or location of the refractory plug. The combustor can operate at conditions typical of an industrial gas turbine, at pressures up to 11 atmospheres, and with the inlet air temperature preheated to 615 K (650 °F). The flow control valves are presently configured to meter combustion air up to 0.68 kg/sec (1.5 lbm/sec), but the facilities can supply combustion air up to 1.8 kg/sec (4 lbm/sec). Tests have already been conducted over the full range of operating conditions, demonstrating acoustic activity at the desired test points. As of this writing, test results showing the effects of operating pressure and inlet air temperature were preliminary, and will be presented in subsequent papers.

Results

Experiments in the atmospheric pressure combustor (Figure 1) have focused on establishing design methods to avoid oscillations from well understood instability mechanisms. Among the various mechanisms that contribute to instability, the variation in fuel or air flow rate may be most common. Reardon (1988) summarized more than 200 cases of combustion oscillations in dump combustors, and found that more than 70 percent of the oscillations were explained by variations in fuel or air flow-rate. Putnam (1971) reported on oscillations from dozens of commercial burners and attributed many of these cases to variations in fuel or air flow-rate. Because of their common occurrence in other burner designs, it is worthwhile to consider how these oscillations may be avoided in lean premix, gas-turbine fuel nozzles.

The processes occurring during fuel-feed variations are shown schematically in Figure 3. This figure considers just fuel-feed fluctuations; variations in the air flow are described by a similar behavior, but are not discussed here. Referring to Figure 3, air is swirled by vanes in the nozzle, which is upstream of the fuel injection point. The time average value of the fuel flow-rate is controlled by an orifice and control valve upstream of the fuel manifold, but the instantaneous value of the fuel flow, $\dot{m}_f(t)$, can vary in response to pressure fluctuations, P(t).

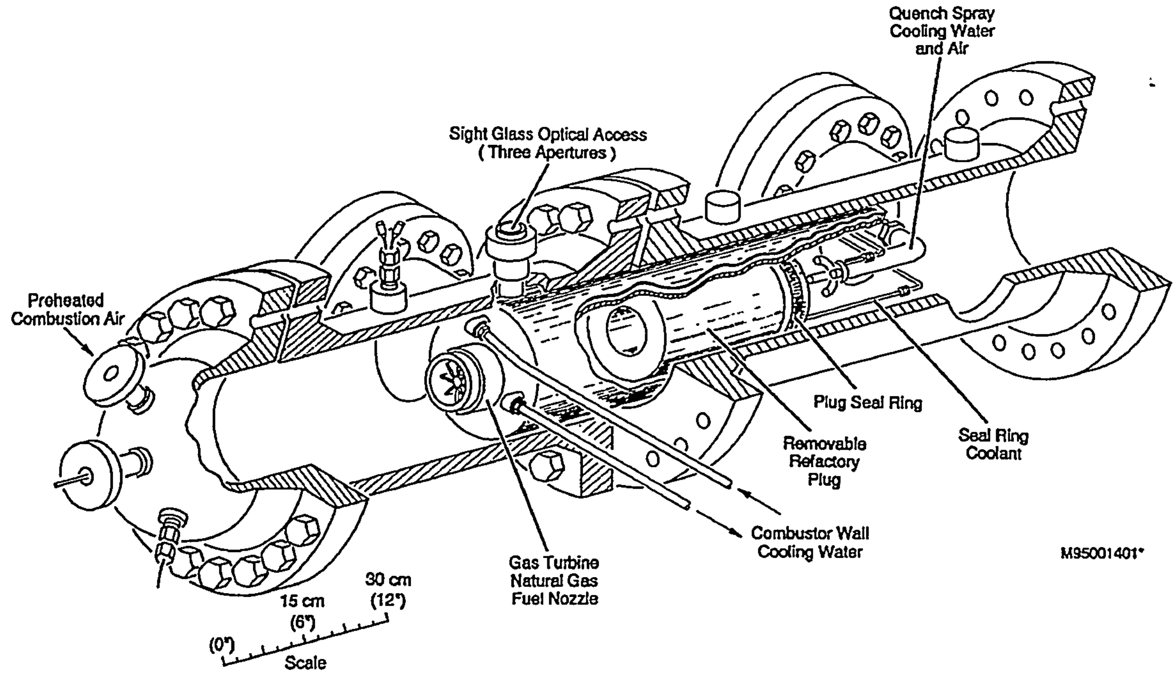

Figure 2. METC Unsteady Gas Turbine Combustor

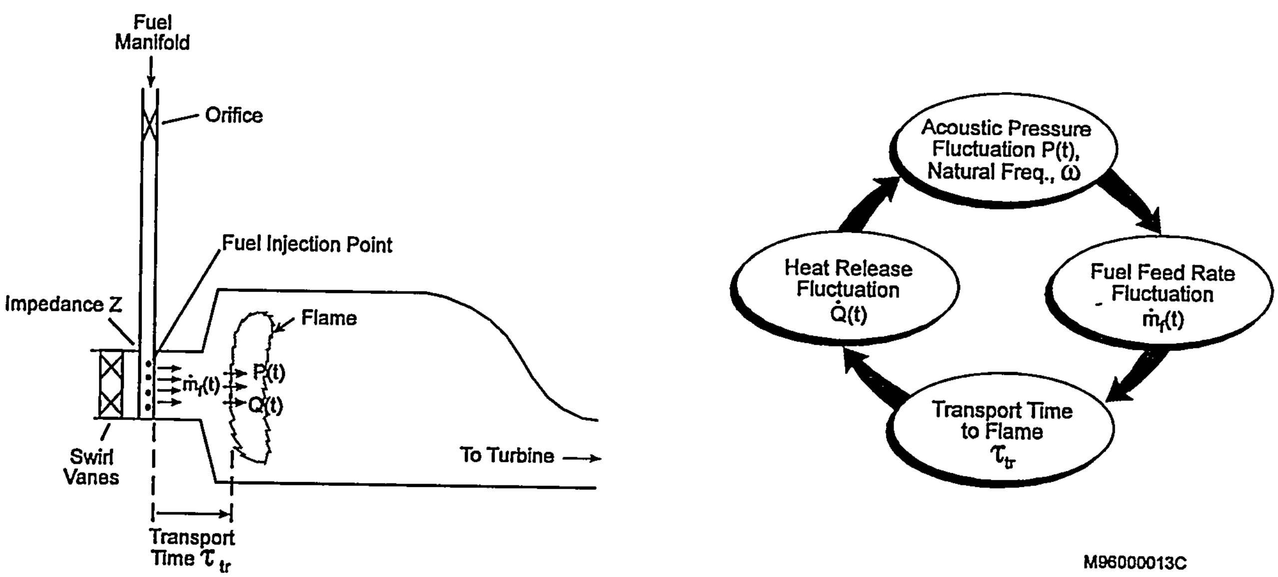

Figure 3. Schematic of Processes Occurring in a Fuel Nozzle/ Combustor During Fuel Feed Instability

For example, if acoustic waves in the combustor momentarily lower the pressure at the fuel injection point, the mass flow will briefly increase, producing a slightly richer fuel air ratio. This rich-mixture pocket will be transported to the premixed flame front in time, τ_{tr}, increasing the heat release rate, $\dot{Q}(t)$. If the accelerated heat release coincides with a high acoustic pressure (i.e., in phase), self-sustaining oscillations are very likely to occur. Conversely, if the heat release variations and the acoustic pressure disturbances are of opposite phase, the combustion should be stable.

These requirements are a statement of the well-known Rayleigh criterion for combustion oscillations. We note in passing that the easiest way to avoid these variations in fuel feed is to simply choke the supply of fuel at the point of fuel injection. A choked flow of fuel would not vary in response to changes in the downstream pressure, preventing the oscillations as described. This approach should be applied whenever possible, but an equal distribution of fuel on multi-nozzle gas turbines typically requires a carefully sized orifice *upstream* of the point of fuel injection, as shown in Figure 3. This limits the pressure drop available at the point of fuel injection. To avoid the penalty of excessively high fuel gas pressures, some tradeoff is necessary between the pressure drop at the fuel injection point and across the orifice. Even where relatively large pressure drops are feasible at the fuel injection point, operation at part load will suffer from reduced pressure drop.

In terms of the parameters shown on Figure 3, we showed in an earlier report (Richards and Yip 1995) how a criterion for oscillating combustion can be developed from the acoustic impedance, Z, of the fuel supply system. As in standard acoustic textbooks, the impedance is a ratio of the acoustic pressure to the change in volume flow of gas (i.e., fuel) flowing out of the fuel injection tube. Using a similar approach a criterion for stable combustion is

$$\text{phase angle } \left\{\frac{e^{-j\omega\tau_{tr}}}{Z}\right\} = \pi,\ 3\pi,\ 5\pi, \ldots \qquad (1)$$

Here, ω is the angular frequency in radians per second, and the transport time is estimated from the bulk flow velocity and the distance between the fuel injection point and the flame. The impedance, Z, is either known for simple geometries, or measured, and depends on the fuel system upstream of the fuel injection point.

In principle, combustion oscillations from fuel feed variations can be avoided by applying equation (1) during nozzle development. The transport time, τ_{tr}, and fuel system impedance, Z, should be designed to produce the requisite phase angle at combustor natural frequencies, ω. In practice, many of these parameters are difficult to estimate, making it difficult to apply equation (1) directly. Instead, it is suggested that equation (1) provides motivation to include some flexibility in nozzle design to allow subsequent changes to the relevant parameters.

As an example of how even slight changes to the fuel system impedance can play a significant role in combustion stability, METC's atmospheric pressure combustor was used to demonstrate certain features of equation (1). As described in Richards and Yip (1995), fuel feed oscillations were deliberately established in this experiment by supplying approximately 10 percent of the premix fuel through a "bypass" port, similar to the fuel injection point on Figure 3. The remaining 90 percent of the fuel was premixed with the air upstream of the fuel nozzle, entering the nozzle through choked orifices. The bypass arrangement allowed a select portion of the fuel to contribute to fuel feed oscillations, while the remainder of the fuel entered at a fixed rate.

To demonstrate the importance of the impedance, Z, the bypass port was manufactured from a variable length tube (Figure 4). The impedance of this tube is calculated from standard acoustic relations and is given by

$$Z = j*\text{constant}*\cot\left(\frac{\omega L}{c}\right); \qquad j=\sqrt{-1}\,, \tag{2}$$

where L is the length of the tube, and c is the speed of sound. Because the cotangent can change from a large positive to a large negative value at specific values of the length, L, equation (2) predicts that the phase angle in equation (1) can abruptly change with the length. This abrupt change may satisfy the requirements to either promote or silence oscillations. Figure 5 demonstrates this behavior from the METC experiment. The measured oscillating combustor pressure (root mean square, RMS) is plotted against the length of the bypass tube. As shown, a change of just 25mm (1 in) can activate the oscillation. This behavior is consistent with equations (1) and (2), and emphasizes the importance of understanding the role of the fuel system impedance before making changes to a fuel nozzle. From a design standpoint, it is suggested that allowance should be made for changes to the impedance should oscillation problems occur during combustor or engine testing.

Ongoing tests with the METC atmospheric pressure experiment have identified other oscillating mechanisms that may occur in turbine fuel nozzles. Figure 6 shows a plot of

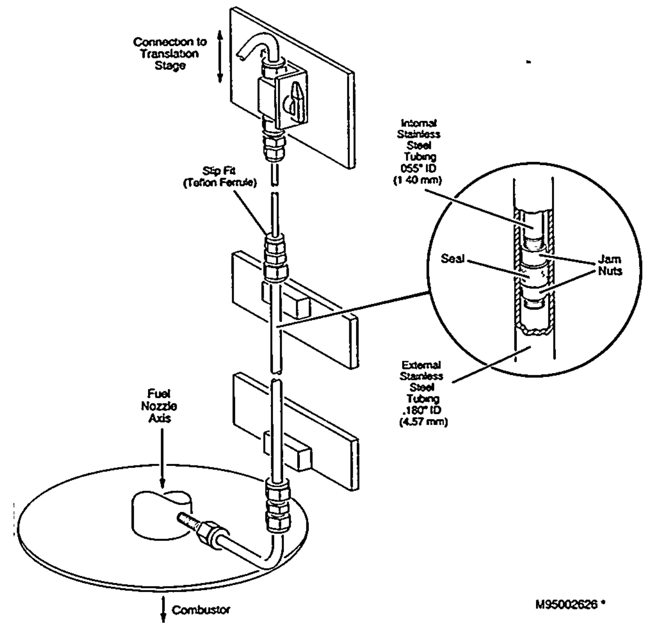

Figure 4. Variable Length Bypass Fuel Tube, Used on the Atmospheric Pressure Combustor (This tube corresponds to the fuel injection point in Figure 3.)

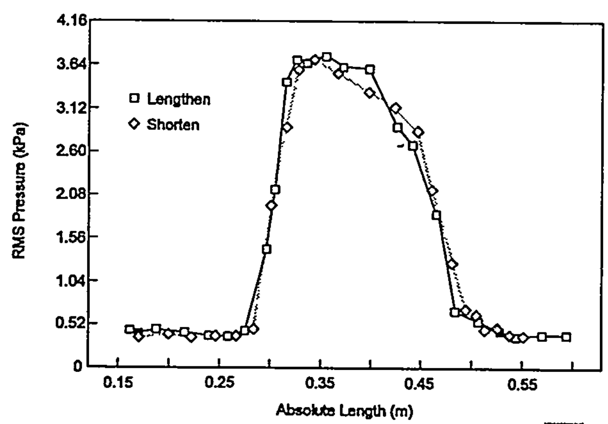

Figure 5. Oscillating Pressure Level (Root Mean Square) as a Function of the Bypass Tube Length

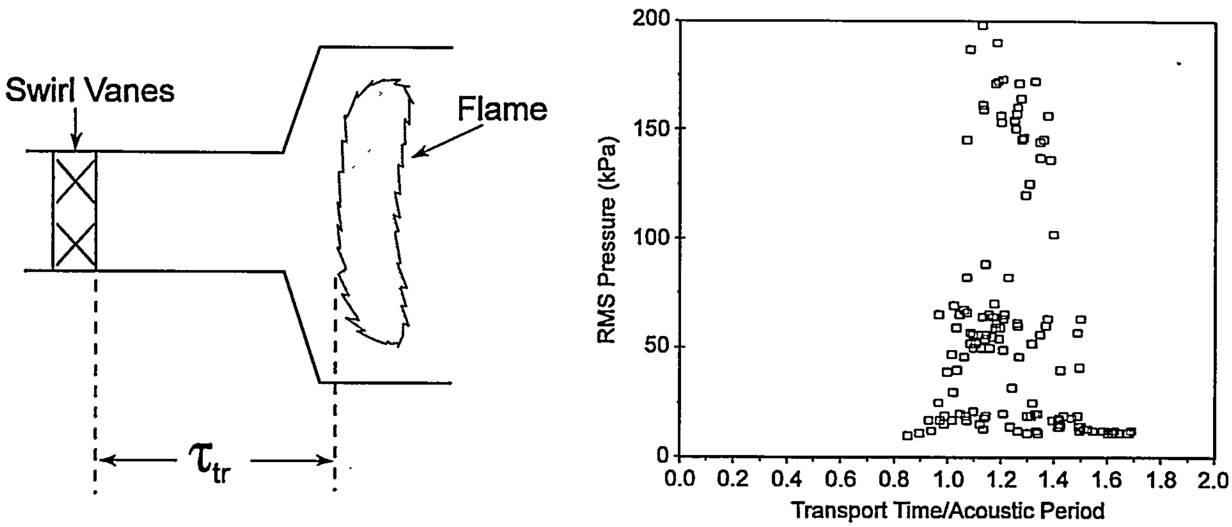

Figure 6. Oscillating Data Attributed to Changes in the Swirl Velocity. Note that transport time, τ_{tr}, is measured from the swirl vanes.

the recorded RMS pressure as a function of the ratio between the transport time, τ_{tr}, *measured from the swirl vanes, as shown,* and the acoustic period. In this nozzle, the fuel and air supply were choked so that fuel feed instability was not possible. The data in Figure 6 were gathered over a range of air flow rates, equivalence ratios, and oscillating frequencies. In spite of the changes in various operating parameters, oscillating behavior was confined to a specific range of time ratios between 1.0 and 1.5.

As described in more detail by Richards and Yip (1995), this behavior suggests that oscillations may result from a coupling between pressure fluctuations and changes in the axial velocity of fuel/air in the nozzle. If the axial velocity fluctuates, the fixed swirl vanes will produce changes in the tangential (or swirling) velocity. Such a change would altar the structure of the flame recirculation zone, and is thought to provide the mechanism needed to sustain oscillations. More data are being gathered to confirm this hypothesis. If this hypothesis is correct, such oscillations can be avoided by locating the swirl vanes along the nozzle axis to produce a time ratio greater than 1.5, or less than 1.0.

Future Work

Continuing tests in the atmospheric pressure combustor (Figure 1) are providing additional confirmation of the role of the swirl vane location in promoting stable combustion. In addition to the fuel feed instability described above, a criterion for avoiding fluctuations in the premixed air supply is being developed. METC is also testing various active control strategies (not discussed here) as an alternative to fuel nozzle design changes. METC's pressurized, unsteady, gas-turbine combustor (Figure 2) is being used to study the effect of operating pressure and inlet temperature on combustion stability. The pressurized combustor allows testing at a scale typical of industrial gas-turbine fuel nozzles.

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