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Gas Turbine Combustion Instability

Authors:
George A. Richards (METC)
George T. Lee (METC)

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Gas Turbine Combustion Instability

Geo. A. Richards
U.S. Department of Energy
Morgantown Energy Technology Center
Morgantown, WV 26505

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BACKGROUND

Gas turbines have traditionally used separate fuel and air entry ports to supply reactants to the primary region of the combustor. This practice produces a stable flame in the primary zone because combustion occurs near stoichiometric, with reactants consumed at a rate controlled by mixing of the fuel and air streams. Subsequent mixing with secondary and tertiary air streams reduces the gas temperature to the desired turbine inlet temperature. This style of combustor (frequently referred to as a diffusion style) has the added advantage that fuel and air are mixed inside the combustor, thereby preventing flashback. Turbine designers have used the advantages of diffusion style combustors for several decades, but tighter regulation of NOx emissions now favors the use of lean premix (LPM) combustion. By premixing fuel and air upstream of the reaction region, LPM combustors avoid locally stoichiometric combustion, eliminating the high temperatures which produce thermal NOx.

Proper design of an LPM combustor requires a high fuel nozzle velocity to prevent flashback, and must provide adequate premixing to avoid locally rich pockets of gas. These requirements could be easily achieved with sufficient pressure drop across the nozzle, but pressure drop must be minimized to maintain overall turbine cycle efficiency. An added requirement is that the flame must not be easily extinguished by a momentary upset (static instability) and it must not oscillate (dynamic instability). Oscillating combustion has emerged as a common problem in LPM combustor design. Oscillations occur when variations in heat release periodically couple to acoustic modes in a combustion chamber, producing significant pressure oscillations. These oscillations must be controlled because the resulting vibration can shorten the lifetime of engine hardware; see Cutrone et al. (1985).

Under the U. S. Department of Energy's Advanced Turbine Systems Program (Parks, 1994), the Morgantown Energy Technology Center (METC) is investigating various approaches to reduce oscillations in LPM combustion. In addition, the South Carolina Energy Research and Development Center has recently sponsored several university projects addressing specific topics in combustion instability (see *Proceedings, 1995*). This paper will provide an overview of the problem of combustion stability in LPM gas turbines, and outline the results of ongoing experiments at METC. The focus of the work is stationary gas turbines burning natural gas, but many of the issues may apply to premix/prevaporize liquid fuel combustion.

OSCILLATING COMBUSTION

Combustion oscillations can be described as shown schematically in Figure 1. A representative lean premix combustion system is shown, with fuel/air mixing occurring in the nozzle, then supplying the LPM flame in the combustion chamber. The variables Q(t) and P(t) represent the *fluctuation* in heat release and pressure[1].

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[1] The fluctuation is the difference between the instantaneous and time average value. These fluctuations are functions of spatial location and time. For clarity in this presentation, we consider just the time dependence. Spatial variations can be accounted for by considering the local values of P and Q, and integrating their effect over the

Oscillations can be treated as a closed loop interaction between combustion and acoustic processes. A variation in heat release Q(t) produces an acoustic disturbance that is reflected by the combustor walls, resulting in a pressure disturbance P(t). The magnitude of this pressure disturbance is reduced by acoustic losses, but can otherwise produce some change in the combustion process altering Q(t). For example, a momentary increase in the combustor pressure will (briefly) reduce the airflow entering via the fuel nozzle. For a constant fuel flow, the reduced air flow will produce a slightly richer mixture, accelerating combustion. Thus, the pressure feedback has produced a variation in Q(t) which starts through the closed-loop cycle again. With the correct timing of the feedback, and sufficiently small losses, the oscillation magnitude can grow to a limit cycle oscillation.

The timing of the feedback can either promote or silence oscillations. The well-known Rayleigh criterion (Rayleigh, 1878) for oscillations states that pressure oscillations should be in-phase with heat release fluctuations to promote oscillations. Conversely, if the pressure is out-of phase with heat release, then the combustion will be stable. In most analysis of oscillating combustion, the phase between pressure and heat release is described by a time lag. In principle, combustors can be stabilized by simply adjusting the time lag to insure that P and Q are out of phase. This technique has been demonstrated in our labs (see below) but the time lag is difficult to predict, and often changes with nozzle and combustion conditions. Because of these uncertainties, Hutt and Rocker (1995) point out that methods to stabilize liquid rocket combustion often begin with the conservative assumption that P and Q are in phase, and then resort to increasing the acoustic losses (or reducing combustion gain).

Remediation of oscillating combustion requires an understanding of the mechanism that produces the variation in heat release Q(t) and the acoustic response P(t). Processes that contribute to variations in heat release are described by Putnam (1971), Harrje and Reardon (1972), Yang and Williams (1995), Candel (1992), and Schadow and Gutmark (1992). Depending on the combustor application, mechanisms include vortex shedding, periodic changes in mixing rates, fuel (or air) system acoustic feedback, changes in liquid fuel evaporation rates, and others. Some of these mechanisms undoubtedly play a role in LPM turbine combustion instability, but the unique features of LPM combustors introduce some differences described later.

The acoustic properties of the combustion chamber determine the acoustic response P(t). Significant progress has been made in understanding the physical processes involved, including recent developments on the non-linear aspects of the acoustic response. Culick (1994) provides both a history of this topic, and more recent analysis of non-linear acoustic behavior; see also the text edited by Yang and Williams (1995). Although the physical processes responsible for the acoustic response are reasonably well understood, practical application of this understanding is difficult to apply during combustor development. The reason is that precise boundary conditions for acoustic calculations are often unknown for complicated nozzle and liner geometries. For example, an LPM turbine combustor is typically developed on a single nozzle test stand. The combustion chamber is usually a simplified version of the final engine configuration using a "sector" combustor for annular designs, or a single "can" combustor. Without special precautions, these test combustors arrangements can have drastically different acoustic boundary conditions than exist on the engine. The result is that test stand evaluation of combustion stability often produces different results than a complete engine test. Thus, it is possible to encounter oscillations late in the development cycle for new combustors, or conversely, to solve single nozzle oscillations which would not appear in the final engine. Either situation increases the cost and development time for new combustors. Richards and Gemmen (1996) discuss this practical aspect of combustor testing, and suggest specific test procedures which may help shorten development time.

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combustor volume.

OSCILLATIONS IN LPM GAS TURBINE COMBUSTORS

The general features of combustion oscillations described above apply generically to most combustion systems. Lean premix combustion oscillations have several features which deserve unique consideration. These features are described below:

Swirl stabilization - Most LPM systems stabilize the flame with recirculation developed by swirling flow. It is well known that vortex shedding from step stabilized (zero-swirl) flames can produce oscillations in afterburners, but there is no comparable understanding for swirl stabilized flames. Sivasegaram and Whitelaw (1991) have published one of the few papers on this topic. Richards and Yip (1995) suggest that swirling flow may indeed present a unique contribution to oscillations in LPM combustors.

Lean operation - By design, LPM combustors are intended to operate close to lean blowoff. Thus, slight changes in mixture strength produce a sizable change in reaction rate. As one example, Keller (1995) points out that acoustic feedback into the fuel system of an LPM combustor can momentarily extinguish a portion of the flame, with the subsequent re-ignition producing very large pressure oscillations.

Pilot flame stabilization - In some cases, the static and dynamic stability of the combustor is enhanced by a pilot flame, operating closer to stoichiometric than the LPM flame. The presence of the pilot serves as an anchor, maintaining combustion even during upsets in the LPM combustion, and mitigating variations in the LPM reaction rate. What is often not understood is that the pilot itself can participate in the oscillation; see the discussion below.

Air entry via the fuel nozzle - Unlike earlier diffusion style combustors, the design of an LPM combustor places virtually all of the air through the fuel nozzle located at the front of the combustor, see Figure 1. Without downstream dilution holes, acoustic losses are very small, thereby increasing the acoustic gain of the combustor. In addition, the design of the fuel nozzle should minimize the air pressure loss for gas turbine thermodynamic efficiency. With a low nozzle pressure loss, relatively small amplitude pressure disturbances will momentarily slow the entry of mixture into the combustor, producing a change in the heat release rate.

Recognizing these distinctive features, tests at the Morgantown Energy Technology Center have focussed on swirl stabilized, piloted, premix combustion. Although tests are still in progress, a combination of experimental testing and various numeric simulations has identified five major mechanisms for oscillations in LPM combustion. These mechanisms will be described during the lecture portion of this paper, and are briefly outlined below.

1) Air supply variation. This mechanism occurs when pressure waves in the combustor produce corresponding changes in the nozzle air flow. With constant fuel flow, the result is a time varying fuel/air ratio.

2) Fuel supply variation. This mechanism is well known in many burner systems, and is the counterpart to the air variation described above, except that the fuel supply varies in response to acoustic feedback.

3)Mixture feed variation. In tests at METC using choked supplies of fuel and air (hence, a constant *mixture* fuel air ratio), oscillations can still be observed at many conditions due to the variation in total mixture flow rate arriving at the flame front. Although the fuel and air stream are choked at the supply point, compression and rarefaction in the fuel nozzle barrel allows a fluctuation in the mixture supply.

4) "Swirl" oscillations. This type of oscillation is still under investigation. A preliminary description

is given by Richards and Yip (1995). Oscillations are believed to result from the transport of swirling flow from the swirl vanes to the combustion chamber. Tests in progress to identify the essential features of this mechanism will be described in the lecture accompanying this paper.

5) Pilot oscillations. For piloted premixed flames, it is often assumed that adding a pilot flame will stabilize oscillating combustion. In fact, tests at METC have shown that acoustic feedback in the pilot fuel or air supply can contribute to oscillations in some circumstances.

Test on both a subscale burner, and commercial scale gas turbine fuel nozzle (Richards and Gemmen 1996) have been consistently described by one of these mechanisms. With an understanding of the relevant mechanisms, it is possible to change the nozzle geometry to adjust the timing of the feedback process outlined in Figure 1, and stabilize oscillations. As just one example, Figure 2 shows how a slight change in the length of the fuel supply system can promote or silence fuel feed oscillations. A variable length fuel tube was added to the barrel of a premixing fuel nozzle as shown. The fuel supply tube was extended through its resonant length as plotted along the x-axis, and the root-mean-square (RMS)of the oscillating pressure was recorded during combustion testing. As shown, the RMS pressure jumps dramatically as the tube length is changed over a distance of less than 25mm. This sharp change is consistent with the transition form leading to lagging acoustic impedance that occurs near resonance. The transition produces a change in the timing of the feedback process and demonstrates that oscillations can be affected by relatively small changes in fuel nozzle geometry. As a second example, Figure 3 compares the effect of adding fuel at different places along the nozzle axis. Several ports were added to the barrel of the fuel nozzle so that fuel could be added at different axial stations along the nozzle, but without changing any other features. The oscillation in these cases was an air supply instability (described above), with a choked supply of fuel added at the particular axial location. As shown, it was possible to produce stable combustion by simply adding the fuel at the correct point along the nozzle axis. Changing the axial location of the fuel addition serves to change the time lag between fuel entry and transport to the flame front. Again, this changes the timing of the feedback loop shown in Figure 1, and can stabilize combustion.

SUMMARY

Combustion oscillations are a common problem in the development of LPM combustors. Unlike earlier, diffusion style combustors, LPM combustors are especially susceptible to oscillations because acoustic losses are smaller, and operation near the lean blowoff produces a greater combustion response to disturbances in reactant supply, mixing, etc. In ongoing tests at the Morgantown Energy Technology Center, five instability mechanisms have been routinely identified in subscale and commercial scale nozzle tests. Changes to the fuel nozzle geometry have shown that it is possible to stabilize combustion by altering the timing of the feedback between acoustic waves and the variation in heat release.

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Figure 1. A schematic of the processes occurring during oscillating combustion in LPM turbines. Oscillations can be treated as a closed loop system, with the combustion and acoustic processes linked together in a periodic cycle.

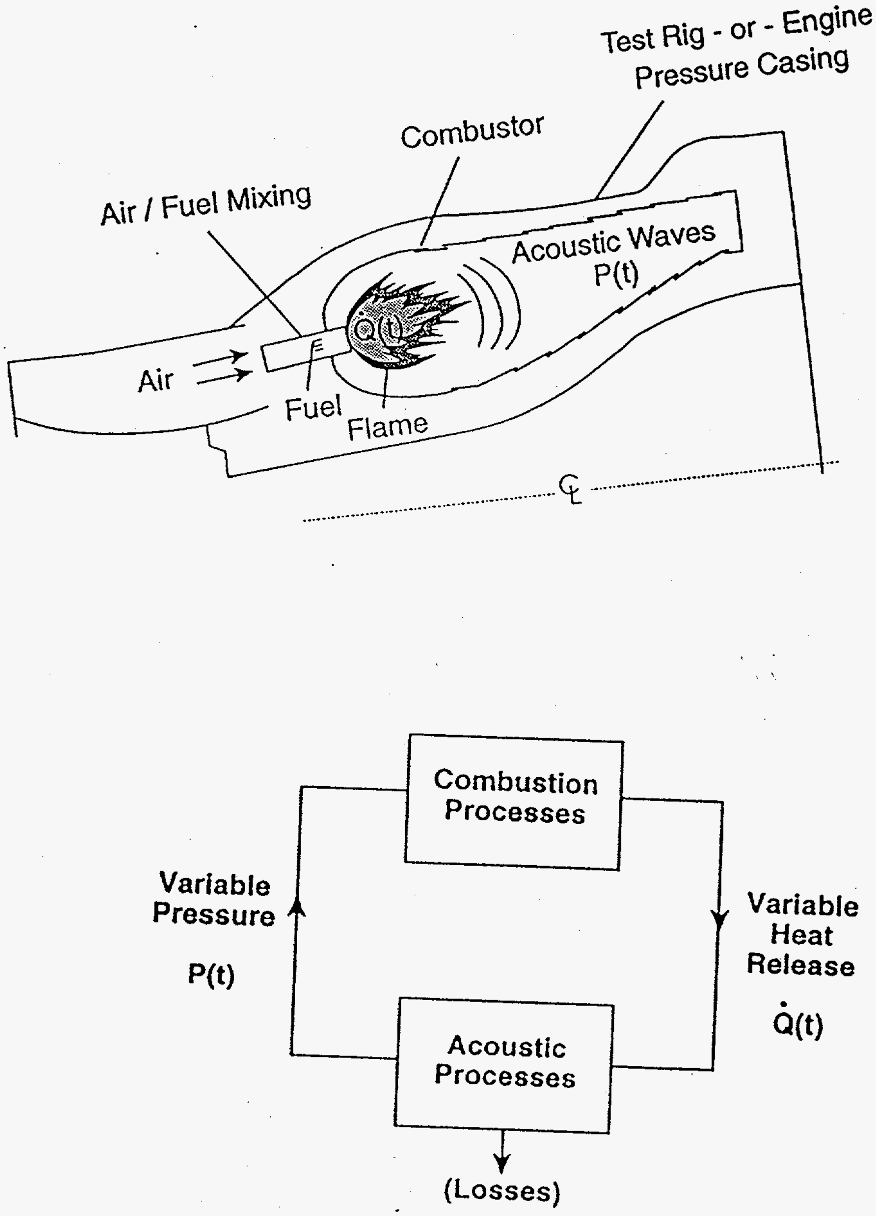

Figure 2. A demonstration of the effect of the fuel supply tube length on combustion oscillations. The fuel supply tube (left) could be extended so that resonance was established in the fuel system Combustion oscillations were then recorded as a function of the tube length (right). Notice the abrupt activation of oscillation as the tube is extended.

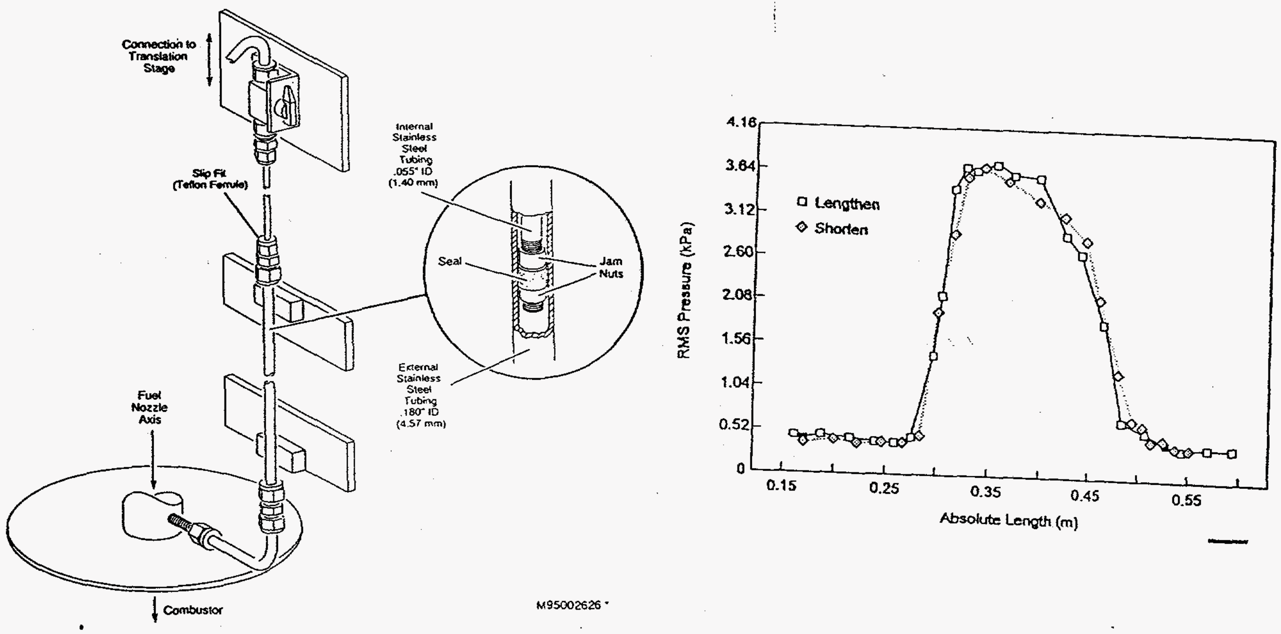

Figure 3. Oscillating combustion pressure recorded as a function of the position of fuel addition. As shown in the left figure, four axial ports were added to the barrel of the LPM combustor. Combustion tests were repeated with fuel injected at the different axial ports. The graph on the right shows that oscillations can be silenced by locating the fuel addition at the correct axial location.