That Elusive Hum

Research is uncovering clues to the oscillations that trouble gas turbines, but the mystery is far from solved.

By Tim Lieuwen and Keith McManus

A LITTLE MORE THAN 60 years ago, the first jet-powered aircraft took to the air, initiating a new era in aviation. About the same time, the first land-based gas turbine was developed for backup power generation. Since then, the gas turbine has made astonishing gains in performance.

Modern power turbines have the highest operating efficiencies and turn out the fewest pollutants among major combustion energy converting devices. In addition, they are attractive because of low capital costs required to bring new systems online. As a result, gas turbines have become the dominant technology for new power generating capacity in the United States and worldwide.

High efficiency with low NO_x comes at a price. Combustion-driven oscillations have damaged this transition piece from a gas turbine.

Demand for land-based systems is at a record high. Anticipating a future demand for electric power that substantially exceeds current capacity, electric utilities worldwide are building new plants and replacing older equipment. As a result, lead times for new machines have increased dramatically, with major gas turbine manufacturers back-ordered for several years.

Modern gas turbines emit substantially fewer greenhouse gases and NO_x (responsible for acid rain) than their older counterparts. These greenhouse gas reductions have been realized primarily through improvements in efficiency; that is, the same amount of energy can be produced with less fuel and thus with fewer pollutant emissions.

In order to further decrease NO_x emissions, the combustor design of modern systems is substantially different from that of older counterparts. Although NO_x formation chemistry is quite complex, its primary source in these systems is often thermal NO_x, which is formed primarily in high-temperature regions when ambient nitrogen reacts with oxygen. This NO_x source can be substantially minimized if the combustion temperature is kept below about 1,800 K (a little hotter than 1,500°C, or 2,700°F).

In older systems, the fuel and a portion of the compressed air were introduced separately into the combustor, where they mixed and burned. With such an arrangement, the flame temperature is quite high and can exceed 2,100 K. The remainder of the air from the compressor then mixes with these hot gases to cool them before they enter the turbine section.

The modern low-emissions systems work differently. The systems premix the fuel and air upstream of the combustor. Furthermore, a significantly larger amount of air from the compressor is introduced into the combus-

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The flame front in a steady flow in a laboratory burner (left) contrasts with the distorted instantaneous flame front during an oscillatory flow.

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tor so that more air is present than is needed to react with the available fuel. In other words, these systems are operated very fuel lean.

While the overall energy released from the reactions in this case remains the same as it would if the mixture were stoichiometrically balanced (assuming the same amount of fuel is burned), it is released into a larger mass of air. As such, the temperature of the combustion products is substantially lower than it would be if the fuel/air ratio were stoichiometric, resulting in far less NO_x production.

Using lean premixed combustion results in very low NO_x emissions; typical values for new machines are under 15 parts per million. However, this mode of combustion introduces a number of new problems.

AVOIDING FLAME FLASHBACK

First, a flammable mixture is created upstream of the combustor. Thus, special consideration must be given in the design to avoid flame flashback. Also, these systems are more prone to blowoff, which occurs when the whole flame simply blows out of the combustor. Special piloting and flame holding designs are needed to address this issue.

In addition, for reasons not entirely understood, these systems are more prone to combustion instabilities. These instabilities are manifested by oscillations in pressure, rate of heat release, and flow rate. They are not new phenomena. They have plagued numerous propulsion and power generation systems, such as solid and liquid rockets, ramjets, and afterburners. An impressive variety of names has appeared to describe them—"screech," "rumble," "buzz," and "humming," to name a few.

Problems associated with instabilities are many. The flow oscillations can cause the flame to blow off in regions where it could otherwise operate. The fluctuations in pressure, occurring several hundred times a second, may cause accelerated wear and cracking.

The basic mechanisms responsible for these instabilities are similar in many ways to feedback encountered in loudspeaker systems. When a microphone detects a signal from a loudspeaker, the sound is amplified and fed back to the loudspeaker to return to the microphone as a louder sound. In the same way, a disturbance in composition of the reactive mixture or local pressure disturbs the flame, which causes fluctuations in heat release that, in turn, excite acoustic waves. These waves propagate away from the flame, but since they are in a closed combustor, reflect off boundaries and re-impinge upon the flame, causing an additional heat release oscillation. This paves the way for a self-exciting feedback loop whose amplitude grows rapidly before saturating into a limit cycle.

These oscillations generally occur at very well-defined frequencies. A combustion chamber in many ways resembles an organ pipe or a resonator. Just as an organ pipe makes a tone of a particular frequency depending upon its length, so a combustion chamber has a resonant frequency of oscillation, depending upon its geometry and the gas temperature. While the source of energy for the oscillations in an organ pipe comes from the air blown through it, combustion instabilities derive their energy from the heat released by chemical reactions.

Less than 0.01 percent of the energy released by the combustion process need be fed into the acoustic field in order to drive 1-psi amplitude pressure oscillations.

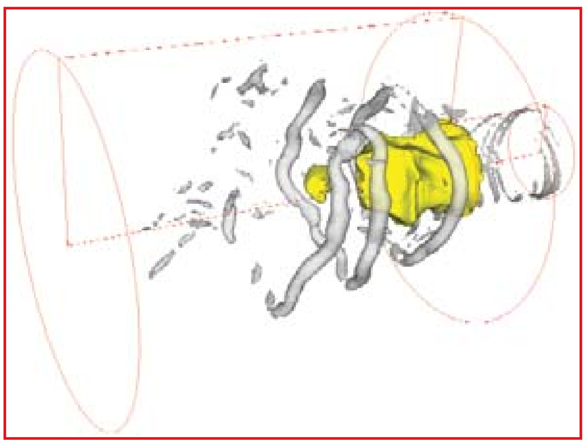
In order to rationally approach the problem of designing stable combustors, engineers need a solid understanding of the mechanisms responsible for them. This is where the problem gets tricky, for while the basic processes responsible for the oscillations are understood, the details are not.

There are several reasons for this state of affairs. First, rational understanding of turbulent combustion is still in its infancy, and combustor designers still must rely primarily on empirical tools for designs. Second, due to the feedback nature of this phenomenon, it is difficult to discern the chicken from the egg. To wit: Are the pressure oscillations in the combustor a result or a cause of the instability? Or, are the instabilities excited by oscillations in mixture composition that, in turn, excite heat release and pressure oscillations?

Engineers have some understanding of the origin of these instabilities. One mechanism that is known to be important arises from oscillations in the fuel/air ratio of the reactive mixture. If the relative flow rates of air and fuel are constant in time, the ratio also remains constant.

However, oscillations during an instability cause disturbances in these flow rates. The composition of the reactive mixture entering the combustor varies in time, creating heat release oscillations and, hence, further flow and pressure disturbances that close the feedback loop.

Understanding the role of this mechanism has provided engineers a good deal of insight into rational design approaches for avoiding instabilities. For example, analysis shows that the conditions under which this mechanism is self-exciting are determined by the characteristics of the premixer, such as the distance between the fuel injection point and the flame. Such insight shows that design of components outside of the combustor itself (in the premixing section) have the most significant impact on the combustor's stability. Without such understanding, engineers might devote more time to less fruitful efforts, such as pursuing ad hoc design changes in the combustor itself.



Computed instantaneous flame position, in yellow, and vorticity contours, in gray, show flame-vortex interaction during an instability.

Unfortunately, improved understanding of this mechanism has not completely eliminated the problem, as other mechanisms also can excite instabilities. The role of these other mechanisms is still the subject of investigation.

Another mechanism believed to be important is the disturbance of the flame by flow oscillations. This mechanism can be understood as follows: If the flow field were completely steady, the flame would also remain more or less stationary. However, the coherent flow oscillations accompanying an instability disturb the flame position, causing the rate of heat release to vary. The details of this mechanism are now fairly well understood in simple laboratory flames, but work must be done to generalize this understanding to the highly turbulent combustors in realistic systems. In addition, other mechanisms also may be important. These may include disturbances of the flame by large-scale, coherent vortical structures or periodic extinction and reignition of the flame.

Besides needing to understand the mechanism responsible for the occurrence of the instability, other important questions also have to be answered. A particularly significant one concerns the processes that control the amplitude at which oscillations saturate.

The reasons for this saturation are similar to the processes of distortion and saturation in a home hi-fi system. As you turn up the knob controlling the volume, above some point the sound output ceases to increase proportionally.

In the same way, as the amplitude of oscillations disturbing the flame increases, the amplitude of subsequent heat release oscillations does not increase proportionally. It has been observed that these instability amplitudes are on the order of a few psi. Why the amplitude saturates at 1 psi, and not at 10 or 100 psi is not entirely clear, however.

In many respects, gas turbine manufacturers are somewhat luckier than their rocket engineering counterparts, who must deal routinely with instabilities that achieve amplitudes of several hundred, or even a thousand psi that can destroy systems in fractions of a second.

A better understanding and, in particular, a capability to predict the instability amplitude, will provide an additional tool to designers. If a system cannot be designed to be completely stable, perhaps it can at least be designed so that the pressure amplitudes are as small as possible.

So what are engineers doing to get around this instability problem? If the mechanisms responsible for the instability are well understood, designing the turbine to be stable at a particular operating condition can be achieved. However, it is generally difficult to develop designs that are stable over a range of conditions.

The inherent variability in ambient air temperature, humidity, and fuel content aggravates the problem. This intrinsic problem with passive approaches has led to the exploration of active control. The basic approach behind active control solutions has some analogies to active noise cancellation. In active noise control applications, a microphone is used to monitor the pressure field. The signal is processed and used to drive a secondary speaker or system of speakers that cancels out the original pressure field.

In combustors, the approach is similar. Rather than using a speaker to cancel out the pressure oscillations, high-bandwidth fuel injectors pulse fuel in an unsteady manner into the combustion chamber. The phase of these fuel pulses is arranged so that their resultant heat release oscillations damp the system oscillations.

Such systems have been demonstrated on a variety of combustors and, with the development of rugged, more reliable sensors and actuators, are rapidly showing their viability.

While much remains to be learned, progress continues. Experimentalists have developed new diagnostic tools for making pertinent measurements in the unsteady, harsh combustor environment. In addition, computational advances in simulating these unsteady flows are providing a more complete picture of the relationships among the myriad of unsteady flow processes and flame propagation. The accuracy of simplified, physics-based models that can be used for design-level decisions is improving.

Combustion dynamics remains a challenging problem, but the large efforts at university, industry, and government labs advance our understanding and bring us closer to dealing with the problem. ■

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