3.1.1
Static and Dynamic Combustion stability

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3.1.1-1 Introduction

The objective of this article is to provide the reader with some background on blowoff and combustion instability, often referred to as a combustor's "static stability" and "dynamic stability". In particular, this chapter will focus upon this phenomenon in lean, premixed combustion systems operating with any of a variety of fuels, such as natural gas or synthetic-gas.

Blowoff refers to the flame physically leaving the combustor and "blowing out" of the combustor. This issue is often referred to as "static stability". Blowoff occurs when the flame cannot be anchored in the combustor. Combustion instability, or "dynamic instabilities" refer to damaging oscillations driven by fluctuations in the combustion heat release rate. These oscillations cause wear and damage to combustor components and, in extreme cases, can cause liberation of pieces into the hot gas path and resulting damaging to downstream turbine components.

3.1.1-2 Static Stability

As the propagation speed of essentially all flames is substantially lower than flow velocities in realistic systems, special flame stabilization systems are necessary to anchor the flame. These include rapid expansions or bluff bodies in the flow, so that there is a re-circulating flow field that recirculates hot products back to the incoming reactants. Swirling combustors introduce this recirculation with purely aerodynamic means - the flow actually reverses direction and forms a recirculation bubble when the fluid has a sufficient swirl number, a phenomenon referred to as "vortex breakdown".

Whatever the stabilization method, a flame can only be stabilized in a combustor over a certain range of conditions, even if those conditions lie within its flammability limits. For example, at a fixed stoichiometry, as the flow velocity is increased, at some point the flame will not be able to remain anchored but will blow off. Alternatively, at a fixed flow velocity, as the equivalence ratio is decreased, at some point the flame blows off.

Predicting blowout behavior is complicated by a lack of understanding of the flame characteristics at the stabilization point. Nonetheless, empirically anchored phenomenological methods for correlating blowout behavior have been reasonably successful. Most approaches consider the ratio of two time scales: a *chemical kinetic time* and *residence time*, τ_{chem}/τ_{res}. The chemical time characterizes how much time is required for the reaction while the residence time characterizes the time which the reactants reside in the reaction zone[1]. This ratio is often referred to as a combustor loading parameter. Simply put, if this residence time is shorter than the chemical time, the flame will blow off. It must be emphasized that the detailed flow and chemical processes are much more complex than this simple picture might suggest; nonetheless, more sophisticated approaches generally reduce to a correlation of this form.

When applied to blowoff limits of premixed flames, this chemical time can be estimated as:

$$\tau_{chem} = \alpha / S_L^2 \tag{1}$$

where S_L and α denote the laminar flame speed and thermal diffusivity, respectively[2]. The residence time is generally scaled as d/U_{ref}, where d and U_{ref} denote a characteristic length scale (e.g., a recirculation zone length) and velocity scale, respectively. Putting this together, blowoff limits should scale with the Damköhler number:

$$Da = \frac{\tau_{res}}{\tau_{chem}} = \frac{S_L^2 d}{\alpha U_{ref}} . \tag{2}$$

Determining the correct length and velocity scale is not straightforward. Note that U_{ref} need not directly scale with approach flow velocity, U_u, due to the acceleration of the burned gas[3]. Since the burned gas velocity scale is given by $U_b=(T_b/T_u)U_u$, then $U_{ref}=f(U_u, T_b/T_u)$. Similar considerations apply for the recirculation zone scale, d. For this reason, prior workers have often had to measure the recirculation zone length in order to use Eq. (2) (e.g., see Ref 6.). Furthermore, the chemical time calculation is complicated by thermal-diffusive effects (i.e., H_2 diffuses much more rapidly than air or other fuels), as the local fuel/air ratio of the mixture may differ from the global average.

While clearly there are important issues such as appropriate choice of length and velocity scale, Damköhler number scalings do a reasonable job in scaling blowout data across a wide range of fuel compositions, as shown in several prior publications. As such, the manner in which the blowoff trends of a system are affected by variations in fuel composition can be inferred from the chemical kinetic times of the mixtures. To illustrate, figure 1, plots the dependence of the chemical time, upon fuel composition of H_2/CO/CH_4 mixtures at a fixed flame temperature of 1900°K. Note the order of magnitude variation in chemical time from the fast H_2 mixtures to slow CO mixtures. One clear implication of this result is that higher hydrogen mixtures will blowoff at leaner equivalence ratios, as can be seen by figure 2, which plots the equivalence ratio of the mixture at blowoff.

It should be emphasized that fluid mechanics, and not just chemical kinetics, must be accounted for in understanding how blowoff limits will vary with composition. Because the flow field and the flame are coupled, variations of the chemistry do impact the flow.

3.1.1-3 Dynamic Stability

Overview

Combustion instabilities refer to large amplitude oscillations of pressure, heat release, velocity, and other variables inside the combustion chamber. They often occur at discrete frequencies associated with the natural acoustic modes of the combustor. Such instabilities have been encountered during the development and operation of most high performance propulsion and power generating devices. They are spontaneously excited by feedback between unsteady heat release and, generally, one of the natural acoustic modes of the combustor. Their occurrence is usually problematic because they produce large amplitude pressure and velocity oscillations that result in enhanced heat transfer and thermal stresses to combustor walls, oscillatory mechanical loads that result in low or high cycle fatigue of system components, and flame blowoff or flashback.

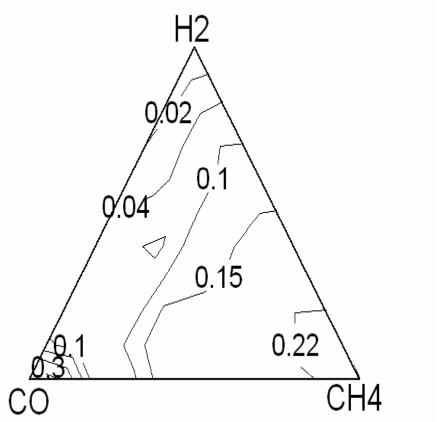

Fig. 1. Dependence of chemical time (ms) upon fuel composition at fixed adiabatic flame temperature of 1900°K [pressure is 4.4 atm with 460K reactants temperature] (reproduced with permission from authors).

Source: Q. Zhang, D. Noble, and T. Lieuwen, “Blowout Measurements in a Syngas-Fired Gas Turbine Combustor,” Annual Pittsburgh Coal Conference (2005).

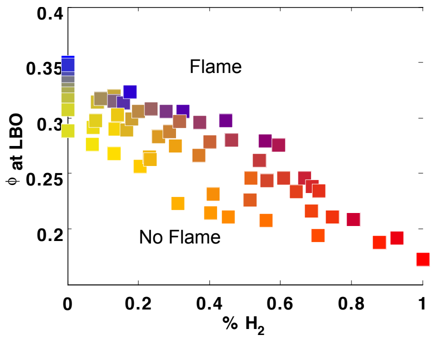

Fig. 2. Dependence of LBO equivalence ratio upon H_2 mole fraction at approach flow velocities of 6 m/s and 4.4 atm combustor pressures, 460 K inlet temperature (reproduced with permisson from authors).

Source: See fig. 1.

A generic feedback loop is shown in figure 3, illustrating the sequence of events responsible for self-excited oscillations in the combustion chamber: (1) Fluctuations in the velocity, pressure, fuel/air ratio, etc. excite a fluctuation in the heat release rate, (2) The heat release fluctuation excites acoustic oscillations, (3) The acoustic oscillations generate the disturbance in Step (1) above, closing the feedback loop. Depending upon the phase between the pressure and heat release (discussed below), the flame may add or remove energy from the acoustic field during each cycle, represented by one complete loop in this diagram. If the energy supplied to the acoustic field by the combustion process exceeds the energy losses of the mode, the acoustic amplitude will grow in time until it saturates, at some limit, cycle amplitude.

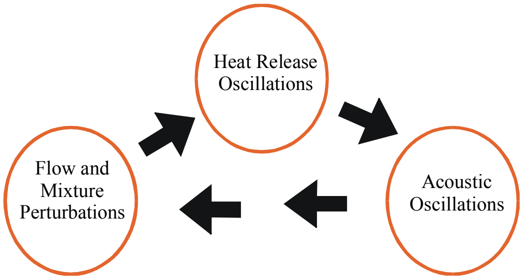

Fig. 3. Illustration of feedback loop responsible for combustion instability.

Generally, combustion instabilities occur at frequencies associated with natural acoustic modes of the combustor. These include, e.g., bulk (i.e., Helmholtz type oscillations), axial, and transverse (i.e., tangential and/or radial) modes (see figure 4). On occasion, however, the oscillations are not associated with a purely acoustic mode and are excited by a coupled "convective-acoustic mode, which occurs at frequencies lower than those of purely acoustic modes. Such oscillations occur when a hot gas packet (due to, e.g., partial flame extinction) or vortex convects through the nozzle, where it excites an acoustic wave that propagates back to the flame[4], exciting another convected wave, thus repeating the process. These types of modes are often encountered in systems that are operating at conditions close to flame blowoff.

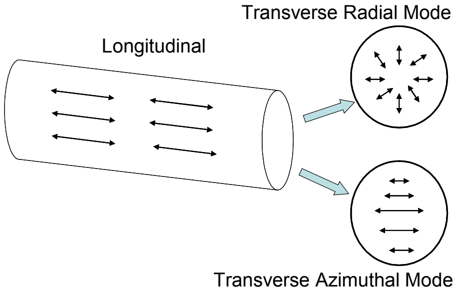

Fig. 4. Longitudinal and transverse acoustic modes in cylindrical combustors.

Why do Instabilities Occur?

In order to understand why instabilities occur, we must understand why the flame adds energy to the acoustic field. Rayleigh's Criterion describes these conditions. Essentially, it states that heat release disturbances add energy to the acoustic field if the heat is added/removed to or from the gas when its pressure is above/below its mean value. This statement is mathematically described by the integral in Eq. (2). This equation shows that the heat addition process locally adds energy to the acoustic field when the magnitude of the phase between the pressure and heat release oscillations, θ_{pq}, is less than ninety degrees (i.e., $0<|\theta_{pq}|<90$). Conversely, when these oscillations are out of phase (i.e., $90<|\theta_{pq}|<180$), the heat addition oscillations damp the acoustic field.

Rayleigh's criterion describes the conditions under which unsteady heat release adds energy to the acoustic field. However, even if energy is transferred from the combustion process to the acoustic field, this does not necessarily imply that the combustor is unstable – this can only happen if the rate of energy supplied by the periodic combustion process to the acoustic field is larger than the rate at which acoustic energy is dissipated within the combustor and/or transmitted through its boundaries.

Having established the conditions under which energy is added to the acoustic field by the flame, we need to consider the mechanisms through which these heat release disturbances are generated. A number of mechanisms can produce heat release fluctuations in gas turbines, as indicated in figure 5. These include:

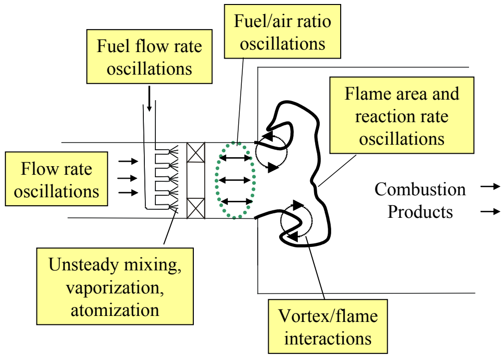

Fig. 5. Potential mechanisms of combustion instability.

1. Fuel Feed Line-Acoustic Coupling. Pressure oscillations in the combustor modulate the pressure drop across unchoked fuel nozzles. This, in turn, modulates the fuel injection rate into the system, causing an oscillatory heat release process that drives the acoustic oscillations.

2. Equivalence Ratio Oscillations[6]. Combustor pressure oscillations propagate into the premixer section where they modulate mixing processes and fuel and/or air supply rates, thus producing a reactive mixture whose equivalence ratio varies periodically in time. The resulting mixture is convected into the flame where it produces heat release oscillations that drive the instability.

4. Oscillatory Flame Area Variation[7]. Interactions of acoustic velocity oscillations with the flame cause periodic variation of the flame area and, thus, a periodic heat addition process that drives the acoustic field.

5. Vortex Shedding[8]. Large scale, coherent vortical structures due to flow separation from flameholders and rapid expansions, as well as vortex breakdown in swirling flows, are often present in gas turbine combustors, as shown in figure 6. The vortical structures distort the flame and cause its surface area to oscillate, thus producing heat release oscillations.

Although the details are excluded here, one can show that in order for any one of these mechanisms to be self-exciting, the characteristic times related to the physical processes responsible for the heat release disturbance must be of similar magnitude as the acoustic period. For example, if the mechanism is equivalence ratio oscillations or vortex shedding, a combustion instability may occur when the following relationship holds:

$$\tau_{convect} + \tau_{chem} = kT \tag{3}$$

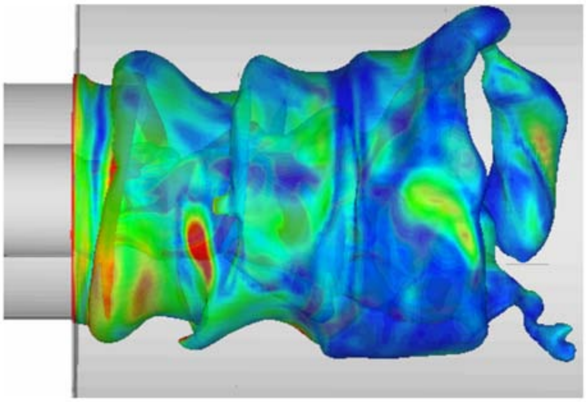

Fig. 6. Computed image of swirling flame distorted by vortical structures (reproduced with permission of Y. Huang and V. Yang).

Source: Y Huang and V. Yang, "Effect of Swirl on Combustion Dynamics in a Lean-Premixed Swirl-Stabilized Combustor," *Proceedings of the Combustion Institute* 30 (2004): 1771-1778.

where $\tau_{convect}$ refers to the time required for either the equivalence ratio oscillation or vortex to convect from its point of formation to the "center of mass" of the flame, τ_{chem} refers to the chemical delay time, T refers to the acoustic period, and k is a series of constants whose value depend upon the combustion chamber acoustics[9].

Fuel composition variations impact this relationship, Eq. (3), by affecting both characteristic times on the left of the equation. Their impact on the chemical time is clear. Their impact on the convective time delay can be better understood from the following equation:

$$\tau_{convect} = (L_{Fl}/n + L_{st})/u \tag{4}$$

where u refers to the mean flow velocity, L_{st} refers to the flame "standoff distance" from wherever the disturbance originates, L_{Fl} is the flame length, and n is a constant that determines the location of the flame "center of mass". For example, an n value of ½ refers to a flame that is effectively concentrated at its midpoint.

Variations in fuel composition impact both the flame standoff location, flame length and the constant n (by altering the flame shape). For situations where the flame temperature remains constant, fuel composition impacts upon the flame standoff location can be approximately inferred from the turbulent flame speed. Increases in turbulent flame speed cause the flame to anchor farther upstream and vice-versa. If the flame temperature varies as well, the situation is much more complex, as the recirculating flow structure can be altered as well in a complex manner.

Similar considerations apply for the flame length, which also scales with the turbulent flame speed. One point worth emphasizing is that no fuel is intrinsically more "stable" or "unstable" than another. In other words, stability is determined by whether the equality in Eq. (4) is satisfied – depending upon flow velocity, flame location, and a variety of other factors, any particular fuel can be either stable or unstable. This point is emphasized because it is sometimes stated, incorrectly, that the addition of hydrogen has a stabilizing influence upon dynamic stability. While hydrogen certainly does have a stabilizing influence on static stability, due to its high flame speed, hydrogen fueled combustors can (and do!) become quite dynamically unstable. One instance where hydrogen addition can promote dynamic stability in general is under near blowout conditions where low frequency dynamic instabilities occur. By promoting a more statically stable flame, hydrogen addition could potentially make these types of dynamic instabilities less problematic.

Growth and Saturation of Instabilities

The amplitude of the instability grows if the rate of energy addition to the oscillations exceeds the rate of energy dissipation by damping processes. As the amplitude of the oscillations increases, the energy addition and dissipation processes become amplitude dependent and the amplitude of the oscillations attains its maximum value when the time average of the energy addition and removal equal one another. The resulting oscillations are referred to as a limit cycle. The objective of this section is to consider the growth and saturation of the instability amplitude.

The mechanisms that initiate combustion instabilities are typically grouped into linear and nonlinear categories. A linearly unstable system is one that is unstable with respect to infinitesimally small disturbances; e.g., a ball perfectly balanced at the crest of a hill.

To further illustrate the dependence of the stability and limit cycle of a system upon the amplitude of the oscillations, A, consider the hypothetical, amplitude dependent, driving, H(A), and damping, D(A) processes, which are described in figure 8. As shown, the "driving" and "damping" curves intersect at the origin, indicating that a zero amplitude oscillation is a potential equilibrium point. This equilibrium point is, however, unstable, as any small disturbance that moves the system away from the origin produces a condition in which H(A) is larger than D(A), resulting in further growth of the disturbance. Because these two curves diverge near the origin, their difference increases with amplitude, implying that the amplitude growth rate increases with amplitude.

Nonlinear combustor processes control the dynamics of the oscillations as the driving and damping processes become amplitude dependent. Figure 8 describes a situation where H(A) saturates and D(A) increases linearly with the amplitude A, thus resulting in an intersection of the two curves at the limit cycle amplitude, A_{LC}.

A nonlinearly unstable system differs from a linearly stable one in that it is stable with respect to small amplitude disturbances but is unstable when subjected to disturbances whose magnitude exceeds a certain threshold value, A_{T}. A simple example of a nonlinearly unstable system is a ball in a depression on the top of a hill. When pushed, this ball returns to its equilibrium point as long as it is subjected to disturbances with amplitude that does not get it over the side walls of the depression. However, for sufficiently large disturbance amplitude, the ball rolls out of the depression and down the hill.

Similar behavior may be observed in combustors. Although nominally stable, if disturbed hard enough, the combustor may become unstable. A typical manifestation of combustors with this type of behavior is hysteresis, where the parameter values where instability occurs differ depending upon whether the parameter is increasing or decreasing. Figure 9 provides an example of the amplitude dependences of H(A) and D(A) that produces the above discussed behavior. In this case, the system has three equilibrium points where the driving and damping curves intersect. Specifically, the damping exceeds the driving when $A<A_{\mathrm{T}}$, indicating that $A=0$ is a stable fixed point, as all disturbances in the range $0< A < A_{\mathrm{T}}$ decay to $A=0$. The next equilibrium amplitude where the driving and damping curves intersect is at the triggering amplitude, $A = A_{\mathrm{T}}$. This is an unstable equilibrium point because any disturbance that shifts the system from this point continues to increase in time. The third equilibrium point, $A=A_{\mathrm{LC}}$, is a stable limit cycle. Thus, in such a system all disturbances with amplitudes $A<A_{\mathrm{T}}$ return to the stable solution $A=0$ and disturbances with amplitudes $A>A_{\mathrm{T}}$ grow until their amplitude attains the value $A=A_{\mathrm{LC}}$. Consequently, two stable solutions exist at this operating condition. The one observed at any point in time will depend upon the history of the system.

Two other phenomena are often observed in unstable combustors under limit cycle conditions. First, is the generation of harmonics. In other words, an instability at 251 Hz generates harmonic oscillations at 502 Hz, and possibly 753 Hz and higher harmonics as well. Second, the presence of oscillations also changes the mean flame position and flow field. For example, the flame may become either shorter or longer.

Unfortunately, the factors that influence the limit cycle instability amplitude are very poorly understood. As such, it is not possible to comment on the influence of fuel composition upon instability amplitudes.

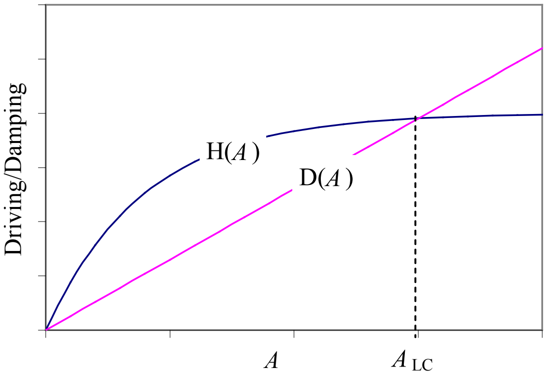

Fig. 7. Hypothetical dependence of the acoustic driving, H(A) and damping, D(A), processes upon the instability amplitude, A.

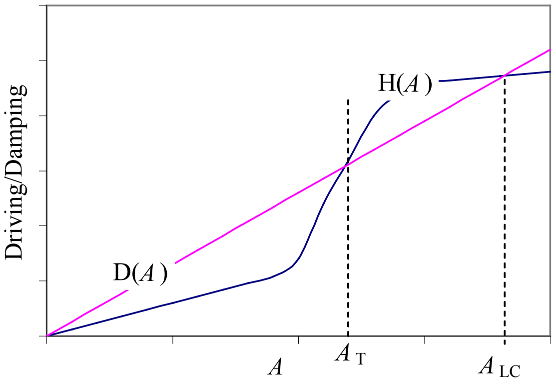

Fig. 8. Hypothetical dependence of the acoustic driving, H(A) and damping, D(A), processes upon amplitude, A, that produce triggering of instabilities.

3.1.1-4 Notes

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9. See note 6 above.

BIOGRAPHY

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