Chapter 3

Thermoacoustic Instabilities Research

In this chapter, relevant literature survey of thermoacoustic instabilities research is included. An introduction to the phenomena of thermoacoustic instability is followed by a survey of thermoacoustic instabilities work carried out in active combustion control research. Various types of instabilities are reviewed in the following section. Modeling of the flame and instabilities are discussed at the end of the chapter.

3.1 Thermoacoustic Instability Definition

The first observation of combustion oscillation was the 'singing flame' which was discovered by Higgins in 1777 [32]. This phenomenon caught the interest of several researchers [33, 34] and they described that high levels of sound can be produced by placing a flame, anchored on a small diameter fuel supply tube in a larger diameter tube. The flame was found to excite the fundamental mode or one of the harmonics of the larger tube. The 'dancing flame' was discovered later by Le Conte [34] where a flame pulses in sync with the audible beats of music. Rijke [35] showed that sound can be generated in a vertical tube open at both ends by placing a heated metal gauze inside the tube. The sound was heard only when the heating element was placed in the lower half of the tube, specifically at a distance of a quarter the tube length from the bottom.

Rayleigh [36] was the first to hypothesize the onset of the instability, and define a criterion for positive coupling based on a phenomenological, heuristic, description of the instability, his explanation was as follows:

> “If heat be periodically communicated to, and abstracted from, a mass of air vibrating in a cylinder bounded by a piston, the effect produced will depend upon the phase of the vibration at which the transfer of heat takes place. If heat be given to the air at the moment of greatest condensation or to be taken from it at the moment of greatest rarefaction, the vibration is encouraged. On the other hand, if heat be given at the moment of greatest rarefaction, or abstracted at the moment of greatest condensation, the vibration is discouraged”.

The Rayleigh criterion can be described by the following inequality:

$$\int_0^\tau \int_0^V p'(x,t)q'(x,t)dvdt > \int_0^\tau \int_0^V \Phi(x,t)dvdt \tag{3.1}$$

where p' and q' are unsteady pressure and heat release, respectively, τ is the period of oscillation, V is the combustor volume (control volume) and Φ is the wave energy dissipation.

Thermoacoustic instability occurs when the inequality in equation 3.1 is satisfied. The LHS and RHS of the inequality describe the total mechanical energy added to the oscillations by the heat addition process per cycle and the total energy dissipated by the oscillation per cycle, respectively. Normally, the acoustic dissipation in combustors can be assumed very small (RHS ≈ 0). Therefore, the Rayleigh criterion commonly used in thermoacoustic instability research is:

$$\int_0^\tau \int_0^V p'(x,t)q'(x,t)dvdt > 0 \tag{3.2}$$

The LHS of equation 3.2 indicates that to satisfy the Rayleigh criterion a specific relationship between p' and q' must exist. p' and q' in phase will lead to instability, and when p' and

q' are out of phase, the effect will be a stabilizing one. Note that the integrals are also spatial, which means that both effects, destabilizing and stabilizing, can occur in different locations of the combustor, and at different times, and the stability of the combustor will be decided by the net mechanical energy added to the combustor. Thermoacoustic instability occurs because of the two-way coupling between combustion exothermicity and acoustics. A dynamics point of view for explaining the instability is that the acoustic field and the heat release source (the flame) are connected dynamically in positive feedback [37].

Combustion instabilities are undesirable since, as observed in large scale gas turbine engines, they are manifested by growing heat release and pressure oscillations. These fluctuations lead to excessive vibrations resulting in mechanical failures, high levels of acoustic noise, high burn and heat transfer rates, and possibly component melting. The oscillations are not undesirable in all systems – the operation of pulsed combustors and ramjet engines inherently depend on the presence of sustained oscillations. The problem has become more relevant because of the stringent low emission and high-power requirements in gas turbines. Modern, low NOx emission gas turbine combustors are prone to these instabilities due to the nature of the flame stabilization mechanisms, the premixing of fuel and air prior to combustion, and the staging of the combustion process. Interest in understanding the physics involved in the instability has grown, and is being applied through passive control means and recently through the use of active feedback control [38].

3.2 Thermoacoustic Instabilities in Gas Turbine Combustion

The problem of thermoacoustic instabilities in low NOx combustors is the result of specific changes made to the diffusion flame combustor to accommodate premixing of air and fuel. In premixed combustors, most of the combustion air is sent through the fuel injector, eliminating the need for downstream combustion air holes that are present in diffusion flame combustors. These downstream air holes provide acoustic damping that reduces the likelihood of oscillations. Also, because of the distributed reaction zone in diffusion flames, it is unlikely that heat-release perturbations couple with the acoustic perturbations. On the other hand in premixed systems, slight disturbances in pressure create immediate changes in the airflow, producing a subsequent change in reaction stoichiometry. Near the lean combustion limit, even minor changes in reaction stoichiometry can lead to significant variations in heat release. If these variations are synchronized with the resonant pressure field, oscillating combustion can be sustained with a frequency from $10\,Hz$ to thousands of hertz.

A variety of complex physical processes may be involved in the development of instabilities, depending on the system characteristics, operating conditions, etc. A large amount of experimental and theoretical work has been carried out to identify the fundamental mechanisms and to analyze the processes. Recent work has relied on detailed experimentation with advanced optical diagnostics and on numerical modeling tools. The objective has been to establish descriptive and predictive models for combustion instabilities. Most of the instabilities observed in gas turbine combustors result from resonant interactions between combustion and coupling modes. A driving process generates perturbations of the flow, a feedback process couples these perturbations to the driving mechanism and produces the resonant interaction that may lead to oscillations. These processes involve time lags because reactants introduced in the chamber at one instant are converted into burnt gases at a later time. Systems with delays are more readily unstable.

Combustion instability occurs when the natural resonant time period of the flow is similar to the characteristic time of the combustion process. The feedback process relates the downstream flow to the upstream region where the perturbations are initiated. As a consequence, acoustic wave propagation is usually responsible for the feedback path. The coupling may also involve convective modes such as entropy waves, associated with temperature fluctuations. Vorticity convected by the flow may also be part of the coupling process. When such fluctuations reach a nozzle on the downstream end of the combustor, they are reflected in the form of upstream propagating pressure waves. It is important to understand the elementary processes of interaction between combustion and waves or flow perturbations (acoustics, convective modes), which may become driving or coupling processes under unstable conditions. McManus et al. [38] and Candel [4] have reviewed the different mechanisms responsible for the generation of combustion instabilities.

Apart from the role of acoustics in the generation of thermoacoustic instabilities, there can be other sources that provoke the occurrence of these kinds of instabilities. Among the many possible causes, some are of special relevance because they cause fluctuations in heat release or generate pressure perturbations. These are:

- unsteady strain rate
- flame/vortex interactions
- acoustic/flame coupling
- interactions of perturbed flame with boundaries
- flame response to incident composition inhomogeneities

The interactions of flames with walls constitute a source of heat release fluctuations. For certain conditions, such interactions can lead to self-sustained oscillations. The driving path that is considered involves surface area fluctuations, unsteady heat release, and acoustic pressure radiation [39]. Vortex structures drive various types of combustion instabilities. In many premixed systems, the ignition and delayed combustion of these structures constitute the mechanism that feeds energy into the oscillation. The process involves two distinct mechanisms. In the first, the flame area is rapidly changing in the presence of a vortex. In the second, the vortex interacts with a wall, or another structure, inducing a sudden ignition of fresh material. An unsteady strain rate can be induced by the resonant acoustic motion acting on the flow. This strain rate may change the rate of heat release because of perturbations in the flame surface area.

Unsteady fluctuations in pressure, temperature, strain rate, and induced curvature, as well as chemical composition, directly influence the rate of reaction in the flame. Unsteady changes in the rates of conversion in the local flame elements or in the available flame surface area are more relevant than the effect of pressure and temperature on the flame. There are two processes that are significant in thermoacoustic instability development: acoustic waves (incoming mass flux fluctuations) and equivalence ratio inhomogeneities. These are not the only possible processes by which incident perturbations drive heat release fluctuations, but they are the most significant.

The effect of acoustics on the flame can be understood by the following coupling mechanism:

$$p_1 \longrightarrow v_1 \longrightarrow A_1 \longrightarrow Q_1 \tag{3.3}$$

where p_1 is the unsteady acoustic pressure, v_1 is the unsteady velocity (mass flux fluctuations), A_1 is the flame area and Q_1 is the unsteady heat release rate from the flame. Several researchers [2, 40, 8] have investigated the effect of acoustics on the flame heat release rate by defining a transfer function between the incident velocity fluctuation and the heat release rate. Experiments and theoretical analysis indicate that certain types of instabilities in lean premixed combustors may be driven by perturbations in the fuel and air ratio [41]. The assumption is that the pressure oscillations in the combustor interact with the fuel supply line and change the fuel flow rate. A positive pressure excursion produces a decrease of the fuel supply at a later instant. This causes a negative perturbation in the equivalence ratio ϕ, which is then convected by the flow to the flame zone.

3.3 Models for Flame Dynamics

An important step in applying passive and active control techniques to full-scale combustors is the development and analysis of low-order dynamical models that capture the main instability mechanisms as well as the parametric bifurcation properties of the system. In particular, to design robust active controllers for combustion systems, one must construct models that contain the fundamental physics of the system. Numerous theoretical and numerical techniques in nonlinear dynamical systems theory have been developed in the research community over the past ten years and can be effectively applied to these reduced order models. These models must be constructed with dynamical systems analysis and control techniques in mind.

The goal for combustion engineers is to develop a model that can rapidly predict the qualitative and quantitative dependence of combustor stability on geometric and fuel composition parameters. Accurately modeling the combustion process response to flow perturbations is a critical component of such a capability. Rapid progress needs to be made in modeling kinematic processes in flame–acoustic interactions. In addition, progress needs to be also made in developing hybrid models that use computational simulations (CFD) to determine various components of the combustor system–flame interactions. The development of accurate, predictive combustion response models for turbulent combustors has not been achieved as yet and remains a key challenge for future workers.

Current needs of modeling flame dynamics is aimed at eliminating the gap between models and experiments, improving the understanding of vortex-flame interactions, identification of nonlinear phenomena responsible for limit-cycle oscillations in combustors, understanding flame-acoustic interactions in realistic geometries and investigating interaction of flames with distributed reaction zones or well stirred reactors.

It is critical that better coordination between models and experiments be achieved. At present, a significant part of the relevant literature consists of essentially decoupled theoretical models or experimental studies, even in rather fundamental configurations [42, 43]. Khanna [1] initiated experimental investigation of velocity perturbations on a flat flame heat release rate. Very few efforts appear to have been initiated to subject the theoretical predictions to experimental scrutiny. Even though highly fundamental studies may be far removed from practical flames, they are prerequisite building blocks toward modeling realistic systems.

The existing theoretical work on vortex-flame interactions is largely numeric. Analytic methodologies for modeling unstable, reacting shear flows need to be developed. The analytical models need to be include the unsteady flow effects on the flame. Predicting the response of flames to finite amplitude waves is not possible as yet. It is not presently clear whether limit-cycle amplitudes in lean, premixed gas turbines are controlled by nonlinear flame front dynamics, the nonlinear response of the equivalence ratio to velocity perturbations in the premixer, chemical kinetic effects, or some other process. Substantial progress could be made by a set of experiments that isolate the key nonlinear processes that need to be focused upon by modelers. Interpretive guidance of these results can be achieved by parallel systematic studies of potential nonlinearities. In addition, effects such as the stabilization or parametric destabilization of flames may cause finite amplitude acoustic oscillations to change substantially the characteristics of the turbulent flame.

Flame–acoustic wave interactions in realistic geometries occur in a very noisy atmosphere, where the flame is a highly perturbed front, even in the absence of coherent acoustic oscillations, and executes large oscillations about its mean position. Any model of the response of laminar flame fronts to velocity, equivalence ratio, or vortical disturbances needs to be generalized to include the effect of the highly unsteady flame. The interactions of flames with thickened flamelets, distributed reaction zones, or well-stirred reactions needs to be considered. Current WSR models are largely based on theory that limits knowledge to phenomena only and have a number of significant conceptual problems.