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Review of Combustion–Acoustic Instabilities

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Abstract

Combustion-acoustic instabilities occur when the acoustic energy increase due to the unsteady heat release of the flame is greater than the losses of acoustic energy from the system. The problem of combustion-acoustic instability is a concern in many devices for various reasons, as each device may have a unique mechanism causing unsteady heat release rates and may have unique boundary conditions. To accurately predict and quantify combustion-acoustic stabilities, the unsteady heat release rate and boundary conditions need to be accurately determined. The present review brings together work performed on a variety of practical combustion devices. Many theoretical and experimental investigations of the unsteady heat release rate have been performed, some based on perturbations in the fuel delivery system particularly for rocket instabilities, while others are based on hydrodynamic processes as in ramjet dump combustors. The boundary conditions for rocket engines have been analyzed and measured extensively. However, less work has been done to measure acoustic boundary conditions in many other combustion systems.

Introduction

Combustion-acoustics interactions arise in many practical devices, such as rocket engines, ramjets, aircraft engines, and gas burners. These interactions have undesirable consequences, varying from small increases in noise to serious mechanical failure caused by enhanced heat transfer rates or resonance. Understanding the effects of pressure fluctuations on combustion and its efficiency is therefore imperative to the successful design and development of practical devices.

The subject of combustion-acoustics interaction has received much attention over the last several decades. However, different types of devices and/or instability mechanisms have been examined by different researchers. For example, Crocco and Cheng[1] developed a time lag model for combustion instabilities in liquid-rocket engines in the 1950's. On the other hand, Giammar and Putnam[2,3] investigated experimentally combustion roar from gas-fueled premixed industrial burners.

Many reviews have appeared that consolidate work performed on a specific type of combustor to provide guidance for development engineers. For example, Culick's[4] review on combustion stability in solid rockets served as a guide for designers. Similarly, Schöyer[5] compiled work performed on combustion instabilities in liquid rockets. Much of the published work is thus device-specific and, as such, not always universally applicable.

This paper represents a preliminary effort to summarize previous work spanning many different devices. Both theoretical and experimental studies are reviewed. The importance and selection of appropriate boundary conditions are also examined. The ultimate goal of the work is to understand, and hence control, combustion-acoustic interactions in advanced, low emission, gas turbine combustors.

Theoretical Work

The term "combustion stability" is used to describe many phenomena, such as blow out and flammability limits, flashback, and resonance established through the interaction of acoustic waves and combustion. This paper is concerned primarily with instabilities arising from combustion-acoustics interactions. Thus, for example, we do not consider the phenomenon of flashback as explained by Lewis and von Elbe[6] and Putnam and Jensen[7], which represents a purely hydrodynamic instability and not an interaction between acoustic waves and combustion.

The fluctuating heat release rate is a source of energy for amplifying acoustic disturbances. A physical interpretation of the interchange of energy between sound waves and unsteady heat release rates was given by Rayleigh[8] for inviscid, linear perturbations. The amplitude of such a sound wave will increase if

$$\int_0^L \frac{(\gamma-1)}{\overline{\rho}\,\overline{c}^2}\overline{Q'p'}\,dx > (p'u'A)_L - (p'u'A)_0, \quad (1)$$

where γ is the specific heat ratio, ρ the density, c the acoustic speed, Q the heat release rate per unit length, p the pressure, x the axial location, A the cross-sectional area, and L the combustor length. The overbar and prime represent mean and fluctuating quantities and the subscripts 0 and L the combustor inlet and exit planes. According to equation (1), acoustic disturbances grow if the net energy gain from combustion is greater than the net energy loss across the boundary. (For viscous, nonlinear perturbations other effects have to be considered.) It is clear from equation (1) that when the heat release rate is in phase with the pressure perturbation, energy is added to the acoustic disturbance.

Bloxidge *et al.*[9] extended Rayleigh's criterion to describe the interaction of unsteady combustion with one-dimensional acoustic waves in a duct. Solutions to the mass, momentum, and energy conservation equations in the pre- and post-flame zones were matched by making several assumptions about the combustion process. In particular, dependent variables, including the heat release rate, were decomposed into mean and fluctuating parts:

$$p = \overline{p} + p', \quad T = \overline{T} + T', \quad Q = \overline{Q} + Q', \quad \text{etc.,} \quad (2)$$

where T is the temperature. For one-dimensional flow in a duct of gradually varying cross-sectional area, the conservation equations for the mean quantities are as follows:

Mass

$$\frac{d}{dx}(\overline{\rho}\,\overline{u}A) = 0 \quad (3)$$

Momentum

$$\overline{\rho}\,\overline{u}\frac{d\overline{u}}{dx} + \frac{d\overline{p}}{dx} = 0 \quad (4)$$

Energy

$$\frac{d}{dx}\left[\overline{\rho}\,\overline{u}A\left(c_p\overline{T} + \frac{1}{2}\overline{u}^2\right)\right] = \overline{Q} \quad (5)$$

In the above equations u is the velocity and c_p the constant-pressure, mass-specific heat of the mixture. As in Rayleigh's work[8], viscosity and thermal conductivity were neglected and only linear perturbations were considered. Also, chemical species conservation equations were not included; that is, the combustion chemistry was not modeled. Bloxidge *et al.*[9] related the ratio of the fluctuating heat release rate to the mean heat release rate with that of the perturbed velocity to the mean velocity. The relationship was determined empirically by measuring fluctuating light emissions from the flame. They solved the mean flow equations and linearly perturbed unsteady equations (see eqs. (7)-(9) below) for one-dimensional flow in a constant-area duct. For a prescribed perturbation frequency, the governing equations were integrated to obtain the growth/decay of the pressure disturbance. The particular eigenvalue was obtained by specifying the pressure fluctuation at the tube exit. Mode shapes were then calculated. They concluded that changes in boundary conditions affect the energy balance of acoustic waves in the combustor.

Abouseif *et al.*[10] also solved the one-dimensional flow equations, but they used a one-step reaction to evaluate the unsteady heat release rate by relating it to temperature and velocity perturbations. Their analysis showed that oscillations arise from coupling between entropy waves produced at the flame and pressure waves originating from the nozzle.

Yang and Culick[11] assumed a thin flame sheet, which is distorted by velocity and pressure oscillations. Conservation equations were expressed in integral form and solutions for the acoustic wave equations and complex frequencies were obtained. As in other models, the imaginary part of the frequency indicated stability regions of the flame.

Paparizos and Culick[12] and Margolis[13] used the method of nonlinear dynamical systems and bifurcation theory to study flame instabilities. They used normal mode analyses to change the governing PDE's to ODE's in time. The temporal amplitudes were determined numerically to obtain limit cycle solutions and various stability limits. Paparizos and Culick's application was concerned solely with rocket-motor instabilities. Since the chemistry is very fast in rocket motors, it was not modeled rigorously but was instead replaced by nonlinear functions. Margolis considered a weakly nonlinear system but was interested in drying seeds in a chamber downstream of the burner. Thus, the combustion was only a source of oscillations in the region of interest, and feedback to the combustion process was not modeled. Margolis concluded that a weakly nonlinear analysis was sufficient to reveal the nonlinear growth of oscillations. Paparizos and Culick, who considered the complete coupled system of evolution equations for complex mode amplitudes, concluded that thorough examination of only a few modes was necessary to understand the nonlinear growth of oscillations.

Activation energy asymptotics, together with a one-step reaction, was used by McIntosh[14], who studied the effects of acoustic forcing and feedback on unsteady, one-dimensional flames. He took advantage of the method of matched asymptotic expansions to find analytical solutions to the highly nonlinear chemical equations. He also assumed, for low Mach number, that the product of density and thermal conductivity was unity. One-dimensional conservation equations for mass, momentum, energy and chemical species were solved in the limit of large activation energy. The acoustic zone was the outer solution, while the combustion zone was treated as the inner solution. A dimensionless parameter in the analysis was the ratio of a characteristic diffusion time to a characteristic acoustic time. For several values of this parameter, asymptotic solutions corresponding to various acoustic wavelengths were obtained. With upstream acoustic feedback to an anchored flame with heat loss, McIntosh concluded that flame stability was altered significantly. Sound emission without feedback was shown to increase regions of stability. Other researchers, for example, van Harten *et al.*[15] and Ledder and Kapila[16], who also used activation energy asymptotics, arrived at similar conclusions.

McManus *et al.*[17], in their review of active control of combustion instabilities, considered a simple model of an acoustically coupled combustion instability. Plane wave solutions were given for velocity and pressure disturbances both upstream and downstream of a flame confined in a tube with a small mean flow Mach number and with open and closed ends. The two ends corresponded to a pressure node and a pressure antinode, respectively. The boundary conditions of vanishingly small pressure and velocity perturbations in the unburned mixture were used, and the flameholder was assumed to be located away from the closed end (a rigid wall). Continuity of pressure perturbations was ensured at the flame front. The model treated combustion as a source of velocity perturbations due to strong dilatation associated with heat release. A time lag model[18,19] for the unsteady heat release rate was used, assuming that the heat release was created uniquely by a velocity perturbation at the flameholder. A nondimensional constant served as a measure of the coupling between the velocity and the oscillating heat release rate. The resulting linear system of four equations was solved to give a nontrivial solution. By setting the determinant of the characteristic (4×4) matrix equal to zero, complex values of frequency were determined. Using their formulation, instability resulted when the imaginary part of the eigenvalue was positive. Other instability mechanisms were also considered: (1) hydrodynamic instability due to the effects of turbulence and vortex shedding, (2) intrinsic flame instabilities due to nonunity Lewis numbers and curvature effects, and (3) shock wave instabilities, wherein fluctuations in the combustion rate may result in the formation of shock waves.

Shyy *et al.*[20] used a high-accuracy TVD scheme to simulate unsteady, one-dimensional, longitudinal, combustion instabilities. However, numerical diffusion was not completely eliminated. Recently, Prasad[21] investigated numerically the interactions of pressure perturbations with premixed flames. He used complex chemistry to study responses of pressure perturbations in one-dimensional combustors. His results indicated that reflected and transmitted waves differed significantly from incident waves.

Darling *et al.*[22,23] added to the work of Bloxsidge et al.[9] by including detailed chemical kinetics in the model for the dynamic heat release rate and allowing a variable area combustor. Their model was constructed by linearly perturbing the compressible, one-dimensional flow equations with heat release. The perturbed quantities were separated into functions of (1) time t, $e^{i\omega t}$, to represent the frequency and growth/decay rate of oscillations, where $i = \sqrt{-1}$ and ω is the complex oscillation rate and (2) axial position, $\hat{p}(x)$. The spatial dependence was further decomposed into real and imaginary parts, $p_1(x) + ip_2(x)$, to represent the phase and magnitude of the oscillations at each axial location, where the functions $p_1(x)$ and $p_2(x)$ were determined by integrating the perturbed equations. Thus

$$p' = \hat{p}(x)e^{i\omega t} = [p_1(x) + ip_2(x)]e^{i\omega t} \tag{6}$$

The equations governing linear, one-dimensional disturbances of mass, momentum, and energy are

$$\frac{d}{dx}\left(\hat{\rho}\bar{u}A + \bar{\rho}\hat{u}A\right) = -i\omega\hat{\rho}A, \tag{7}$$

$$\frac{d}{dx}\left(\hat{p} + \hat{\rho}\bar{u}^2 + 2\bar{\rho}\bar{u}\hat{u}\right) = -i\omega\left(\hat{\rho}\bar{u} + \bar{\rho}\hat{u}\right) \tag{8}$$

and

$$A\frac{d}{dx}\left[\left(\hat{\rho}\bar{u} + \bar{\rho}\hat{u}\right)\left(c_p\bar{T} + \frac{1}{2}\bar{u}^2\right) + \bar{\rho}\bar{u}\left(c_p\hat{T} + \bar{u}\hat{u}\right)\right] = \hat{Q} - i\omega A\left[\hat{\rho}\left(c_v\bar{T} + \frac{1}{2}\bar{u}^2\right) + \bar{\rho}\left(c_v\hat{T} + \bar{u}\hat{u}\right)\right] \tag{9}$$

where c_v is the constant-volume, mass-specific heat of the mixture. The difference between this model and those of Bloxsidge *et al.*[9], Paparizos and Culick[12], Margolis[13], and Abouseif *et al.*[10] lies in the heat release rate calculation. The heat release rate per unit length at a given axial location was computed as a function of temperature, density and chemical composition at that point:

$$Q = \bar{Q} + Q' = f(T, \rho, \sigma_i), i = 1, \ldots, NS \tag{10}$$

where σ_i is the mass-specific mole number of species i, that is, moles of species i per unit mass of mixture, and NS is the total number of chemical species (reacting and inert). The perturbation in heat release rate was given by

$$Q' = \left(\frac{\partial Q}{\partial T}\right)_{\rho} T' + \left(\frac{\partial Q}{\partial \rho}\right)_{T} \rho'. \tag{11}$$

The partial derivatives $\partial Q/\partial T$ and $\partial Q/\partial \rho$ were assumed to be functions of axial position only, and not time. Therefore, for a given mean flow, it was necessary to calculate these terms only once at each spatial location. The partial derivatives in equation (11) were obtained by using a modified version of LSENS, the Lewis Kinetics and Sensitivity Analysis Code[24,25], which uses the backward differentiation formula method, as implemented in the code LSODE[26]. Thus the chemical reaction mechanism (i.e., the chemistry) could be as complex as desired—the solution procedure is discussed by Darling *et al.*[23].

In a simpler model, Darling *et al.*[22] assumed negligible mean Mach number; that is, the mean flow velocity was assumed to be small relative to the sonic speed. The perturbed equations were then easily solved by integrating the real and imaginary components of the following equations:

$$\frac{d\hat{u}}{dx} = -\frac{i\omega\hat{p}}{\rho} - \frac{\hat{u}\dfrac{d\bar{\rho}}{dx}}{\rho}, \tag{12}$$

$$\frac{d\hat{p}}{dx} = -i\omega\bar{\rho}\hat{u}, \tag{13}$$

$$\hat{T} = \frac{1}{i\omega A c_p \rho}\left(\hat{Q} + i\omega A\hat{p} - Ac_p\bar{\rho}\hat{u}\frac{d\bar{T}}{dx}\right) \tag{14}$$

$$\hat{\rho} = \frac{\hat{p}}{RT} - \frac{\bar{\rho}\hat{T}}{T}, \tag{15}$$

where R is the gas constant. The model was used to predict regions of stability and growth/decay of disturbances in a constant-area, premixed combustor. Various boundary and flow conditions were considered. In general, lower reflectivities resulted in more stable systems, because more acoustic energy was transmitted across the boundaries than generated from combustion. The reflectivity level when the system became unstable was found to be a function of frequency, geometry, and flow conditions.

Acoustic Region

In general, the scales of applied disturbance differ from those of the flame. In particular, the characteristic length scale of a typical disturbance is its wavelength L_0. An appropriate time scale is L_0/c_0, where c_0 is the frozen sound speed. We define the dimensionless quantity τ as

$$\tau = \frac{l_0/v_0}{L_0/c_0}, \tag{16}$$

where l_0 is the normal flame thickness and v_0 the flame speed. The response of a flame to a particular disturbance is dependent on τ, the ratio of a characteristic diffusion time to a characteristic acoustic time. If this ratio is small compared to unity, the flame structure may be treated as quasi-steady; however, the flame becomes unsteady if the ratio is of order unity. In the limit of small frequency, the wavelength is much larger than the flame thickness and the method of large activation energy can be employed to study combustion instabilities[16,27].

A recent survey by Oran and Gardner[28] on combustion-acoustic interactions also explained many studies in terms of characteristic length and time scales of acoustic disturbances.

Experimental Studies

Experimental studies of combustion instabilities have had varied objectives. Some researchers studied mechanisms and modes of instabilities. Others quantified a particular instability mechanism. And yet others were concerned with the noise produced by combustors as an environmental problem. Many mechanisms have been considered that relate pressure perturbations within a combustion system to the heat release from the flame. The unsteady heat release rate was sometimes caused by hydrodynamic instabilities, such as vortex shedding, which coupled with the acoustics of the combustor. In other cases, fluctuations in the fuel injection system resulted in unsteady heat release rates, which coupled with the chamber acoustic modes. The fluctuating heat release rate has also been controlled by actively modulating the fuel flow rate. We now discuss some experimental equipment used to study combustion-acoustic interactions and the results of these studies.

Giammar and Putnam[2] performed a comprehensive study of noise generated by gas-fired industrial burners and made several important observations. Flow noise was sometimes more intense than combustion roar, which tended to have a characteristic frequency spectrum. Turbulence was amplified by the flame. The noise power varied directly with combustion intensity and also with the product of pressure drop and heat release rate. Combustion noise depended on the material used in the refractory tiles of the burner (i.e., the acoustic boundary conditions). The authors later correlated the peak frequency of the combustion noise spectrum from premixed burners to the firing rate and the product of pressure drop and heat release rate[3].

Karchmer[29] correlated the noise emitted from a turbofan jet engine with that in the combustion chamber. This work is significant for two reasons. First, it quantified how much of the noise from an engine originates in the combustor. Second, it gave a measure of the transmissivity of the downstream boundary of the combustor. Karchmer also correlated near-field pressure oscillation measurements with far-field acoustic measurements and discovered that their interrelationship was a function of the square of the frequency.

In Davies' investigations[30] two types of combustion instabilities were most commonly observed: (1) low-frequency, large-amplitude pressure instabilities at frequencies of between 50-500 Hz, associated with rumbling noise and (2) high-frequency, small-amplitude instabilities with frequencies of between 2,500-4,000 Hz. In the first type of instability, which was the focus of the work, at least two modes were observed. In the first mode, the combustion process oscillated at a frequency of about 130 Hz between two limits: a thin flame zone near the dump plane of the combustor and a broken flame that occupied the entire combustor length. In the second mode, the instability was exhibited as regular shedding of hot spots from the recirculation zone at a frequency of about 340 Hz and the flame occupied the entire combustor length. It is not clear, however, if these features persist under high pressure conditions.

Schadow *et al.*[31] studied coaxial and side dump combustors, in which the premixed fuel-air was injected at an angle of 60 degrees from the axis. Schlieren photography was used to visualize the flow. The authors were concerned with acoustic modes in the combustion chamber and with the response of the shock close to the combustor inlet to pressure fluctuations in the chamber.

Mahan[32] provided a review of work on noise emissions from gas-fired burners. Different mechanisms of sound production were proposed, such as instabilities in the feed lines and coupling of the turbulent mixing of cool reactants and hot products with the acoustic modes of the combustion chamber. Turbulent mixing mechanisms were primarily considered, such as the shedding of vortices, convecting unburned fuel into hot regions, where it burned and acted as a moving acoustic source.

The goal of Samaniego *et al.*[33] was to identify instability modes in side dump combustors. The global heat release rate was determined by measuring light emissions from C_2 and CH radicals. This method appears to be typical for measuring dynamic heat release rates. Schlieren photography was used for flow visualization. Dynamic pressure was measured at the closed end of the combustion chamber with a microphone mounted in a semi-infinite waveguide. Fluctuations in inlet velocity were measured with a hot film anemometer. They identified modes of instability for normal injection. The flapping and periodic impingement of the jets were coupled with the quarter wavelength acoustic mode of the combustion chamber. For fuel-rich cases the jet impingement was in phase with the global heat release rate. For lean flames, however, the two quantities were almost exactly out of phase with each another.

Boundary Conditions

The Rayleigh criterion says that a system will be unstable if the amplification of the acoustic wave by the flame is greater than the acoustic energy lost at the boundaries (and, in general, by viscous dissipation as well). Thus, an accurate measure of energy lost at the boundaries is crucial to predicting/analyzing combustion-acoustic instability. In addition, perturbations in the fuel delivery system can affect the unsteady heat release rate and, thus, affect the amplification of acoustic waves and system stability. The outlet, the inlet, the sidewalls, and the fuel injectors are all important boundaries.

Crocco and Cheng[1] analyzed admittances of choked rocket nozzles and later Crocco and Sirignano[34] performed a more comprehensive analysis. The latter authors' work on calculating admittance coefficients was relevant to the liquid-fueled rocket engine. One of their conclusions was that asymptotic analysis may provide a better procedure than numerical interpolation for determining nozzle admittance.

Zinn *et al.*[35] experimentally determined liquid-rocket nozzle admittances. Samaniego *et al.* used an impedance tube with one-dimensional mean flow to verify the analytical predictions of admittances from choked nozzles. Mixed longitudinal and tangential modes were tested. There was good agreement between the theoretical admittances (of Crocco and Sirignano[34]) and those measured in the impedance tube, indicating that the analytical values were suitable boundary conditions.

Feiler and Heidman[36] developed a model to predict the response of gaseous-hydrogen injection to perturbations in the combustion chamber. Their model used a lumped parameter acoustic model of coaxial injector elements. The supply dome was treated as a capacitance, the annular entrance had both a resistive and inductive component, and the final orifice was modeled as a resistance. A time lag model was used to model the perturbations in heat release rate. Feiler[37] later used this model to predict the effects of various parameters on rocket motor stability. The density of the injected hydrogen was found to be very important in determining stability limits. The system stability increased with decreasing hydrogen density.

The injector response model of Feiler and Heidman was experimentally verified by Janardan *et al*[38]. A modified impedance tube was used to measure the response factor of coaxial injectors, through which gas was flowing. The pressure drop across the orifice was maintained to simulate conditions in an actual engine. An acoustic driver provided harmonic oscillations from 150 Hz to 800 Hz, and the resulting standing wave pattern was measured to determine the admittance of the injectors. The experimental data was found to match the analytical model well, when the model was modified slightly. The orifice length used in the model was replaced by an effective length to account for the end correction of the orifice. In addition, Janardan *et al.* varied injector parameters to experimentally determine the effect on the injector response. They found that variations in the orifice pressure drop had little effect on the resonant frequency of the injector, while increases in the open-area ratio of the injector increased both the injector response factor and the resonant frequency.

For high frequency oscillations, the wavelengths of disturbances are on the same order or smaller than the dimensions of the fuel and oxidizer feed systems. Thus, to study high frequency instabilities, acoustic propagations in the feed systems themselves need to be considered. Priem and Breisacher[39] extended the lumped parameter approach of Feiler and Heidmann to model oscillations with frequencies up to 14,000 Hz. Acoustic propagations in the feed systems were added. Only axial modes were considered in the delivery tubes, since their diameters were very small relative to the acoustic wavelength. However, tangential modes were considered in the feed system manifolds. Using this improved model, several conclusions were made. Decreasing the fuel velocity improved stability when chamber oscillations were coupled with the oxidizer feed system, but increasing the fuel velocity improved stability when chamber oscillations were coupled with the fuel feed system.

For a liquid-fueled combustor, additional processes occur between fuel injection and combustion, namely atomization and vaporization. Heidmann and Groeneweg[40,41] developed a model for the dynamic response of liquid jet breakup and atomization to acoustic vibrations. They concluded that the atomization process may be the rate-controlling step in dynamic systems, because small drops, which can lead to rapid burning, were formed. Also, Heidmann and Weiber[42] developed a model to predict the response of vaporization to acoustic disturbances.

Acoustic liners are often used on side walls to damp vibrations. Typically, the cavities in acoustic liners look like simple resonators. However, as Bell *et al.*[43] showed, the admittance of acoustic liner cavities is altered when acoustic waves do not travel normal to the cavity entrance. In addition, at high amplitudes, above 120 dB, nonlinear effects, such as vortices forming at the cavity entrance, were important. Thus, the response of the liner to acoustic disturbances was a function of both frequency and amplitude for the large disturbances found in rocket motors and gas turbine combustors. Bell *et al* measured admittances of acoustic liners using a modified impedance tube, which allowed a mean flow, and had an acoustic driver to excite mixed tangential-longitudinal modes from 600 Hz to 1100 Hz.

From an experimental viewpoint, there is another concern. Not all of the pressure oscillations measured locally within a combustor propagate as acoustic waves. For a pressure oscillation to propagate, the divergence of velocity must be nonzero. In addition, for high frequencies, a single point measurement is not sufficient to determine the character of the pressure disturbance at a given axial location. A study of this problem was given by Strahle *et al.*[44], who correlated internal and external noise from a combustor that exhausted directly to the atmosphere.

Conclusions

The problem of combustion-acoustic instability is a concern in many devices for various reasons. To accurately predict and quantify combustion-acoustic stabilities, the unsteady heat release rate and boundary conditions need to be accurately determined. Many theoretical and experimental investigations of the unsteady heat release rate have been performed, some are based on perturbations in the fuel delivery system particularly for rocket instabilities, while others are based on hydrodynamic processes important in ramjet dump combustors. The boundary conditions for rocket engines have been analyzed and measured extensively. However, less work has been done to measure acoustic boundary conditions in other combustion systems.

Acknowledgments

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Combustion-acoustic instabilities occur when the acoustic energy increase due to the unsteady heat release of the flame is greater than the losses of acoustic energy from the system. The problem of combustion-acoustic instability is a concern in many devices for various reasons, as each device may have a unique mechanism causing unsteady heat release rates and may have unique boundary conditions. To accurately predict and quantify combustion-acoustic stabilities, the unsteady heat release rate and boundary conditions need to be accurately determined. The present review brings together work performed on a variety of practical combustion devices. Many theoretical and experimental investigations of the unsteady heat release rate have been performed, some based on perturbations in the fuel delivery system particularly for rocket instabilities, while others are based on hydrodynamic processes as in ramjet dump combustors. The boundary conditions for rocket engines have been analyzed and measured extensively. However, less work has been done to measure acoustic boundary conditions in many other combustion systems.

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