

Thermoacoustic Instability in Combustors

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Keywords

thermoacoustic instability, combustion instability, acoustics, aeroacoustics, reacting flows, combustors, burners, acoustic damping

Abstract

Thermoacoustic instability is a flow instability that arises due to a two-way coupling between acoustic waves and unsteady heat release rate. It can cause damaging, large-amplitude oscillations in the combustors of gas turbines, aeroengines, rocket engines, etc., and the transition to decarbonized fuels is likely to introduce new thermoacoustic instability problems. With a focus on practical thermoacoustic instability problems, especially in gas turbine combustors, this review presents the common types of combustor and burner geometry used. It discusses the relevant flow physics underpinning their acoustic and unsteady flame behaviors, including how these differ across combustor and burner types. Computational tools for predicting thermoacoustic instability can be categorized into direct computational approaches, in which a single flow simulation resolves all of the most important length scales and timescales, and coupled/hybrid approaches, which couple separate computational treatments for the acoustic waves and flame, exploiting the large disparity in length scales associated with these. Examples of successful computational prediction of thermoacoustic instability in realistic combustors are given, along with outlooks for future research in this area.

1. INTRODUCTION

Thermoacoustic instability is a flow instability that arises due to a two-way coupling between acoustic waves and unsteady heat release rate. Its practical occurrence is within combustors, where the unsteady heat release rate is associated with unsteady combustion, and hence it is often termed combustion instability. It is invariably unwanted, as it often leads to large and damaging flow and heat release rate oscillations, which can cause structural damage, excessive vibration and noise, flame flashback, flame blow-off, and other deterioration in a combustion system's performance.

The combustors of gas turbines, aeroengines, rocket engines, domestic boilers, afterburners, etc. can all exhibit thermoacoustic instability. The phenomenon first came to prominence due to its occurrence in rocket engines, including the F-1 rocket engines for the Apollo missions (Oefelein & Yang 1993). Over recent decades, it has been a major issue for gas turbine manufacturers (both land-based and aeroengines), as the use of lean premixed combustion for low NO_x emissions significantly exacerbates thermoacoustic instability problems (Mongia et al. 2003). Whether thermoacoustic instability is a problem generally becomes apparent late in the design and development process, making modifications for its mitigation difficult and costly (Poinsot 2017). The current need to decarbonize energy generation and aviation is driving a transition toward carbon-free fuels, such as hydrogen and ammonia, as well as other sustainable fuels, such as sustainable aviation fuel, with new designs of fuel injectors, burners, combustors, and cooling systems potentially needed to accommodate these. New problems with thermoacoustic instability are likely to arise; for example, the use of hydrogen in fuel can sometimes increase the propensity to instability (Beita et al. 2021). However, the need for redesigns also creates new opportunities for mitigating instability and a more urgent need for accurate computational predictions that can help inform the design process.

Returning to the underpinning mechanism, thermoacoustic instability arises due to a two-way coupling between acoustic (sound) waves and unsteady heat release. For example, background sound disturbances incident on a flame will cause oscillations in the heat release rate—this may be through local changes in the fuel–air ratio or hydrodynamic oscillations causing flame-front movement (Candel 2002, Ducruix et al. 2003, Lieuwen 2003). Unsteady combustion is an efficient acoustic source and in turn generates new acoustic waves, which propagate away from the flame (Ducruix et al. 2003, Dowling & Mahmoudi 2015). These partially reflect from the boundaries of the combustor, arriving back at the flame where they further perturb the heat release rate. Under some conditions, the resulting cycle will lead to oscillations of certain frequencies successively growing in amplitude—thermoacoustic instability. It is noted that intrinsic thermoacoustic modes arise from a slightly different coupling mechanism that does not require acoustic reflection from boundaries—the works by Hoeijmakers et al. (2014), Emmert et al. (2015), and Silva (2023) provide more details on these. Thermoacoustic instability is typically linear, meaning that small perturbations grow in time, eventually reaching levels that introduce nonlinear effects that limit further growth. Self-excited oscillations occur, often in the form of limit cycle oscillations dominated by a single oscillation frequency, although more complex nonlinear dynamics are possible (Juniper & Sujith 2018).

The key flow phenomena are thus the acoustic waves and the flame's unsteady heat release rate, which depend upon acoustic propagation, acoustic reflection, turbulent reacting flow, vortex dynamics, combustion chemistry, heat transfer, etc. These diverse flow physics span a very large range of length scales and timescales. For example, the length scales relevant to the flame include turbulent flame-front wrinkling and even smaller chemical reaction scales, while the acoustic waves typically have wavelengths of the order of a meter or more. The flame-front chemical

reactions are very fast, but instability develops over long timescales. The complexities of real systems introduce effects such as elevated pressure, elevated temperature, and often interactions of multiple flames and/or combustors.

It is for these reasons that achieving accurate thermoacoustic instability predictions for designs of real combustors remains a challenging and expensive endeavor. Direct computational approaches, in which simulations directly resolve all of the most relevant scales and flow physics, are possible (Poinsot 2017). Alternative approaches instead apply separate computational treatments to the two key phenomena—the acoustic waves and the flame—and then couple these. The use of such hybrid/coupled methods has the benefit of allowing different computational tools to be tailored to the relevant flow scales and flow physics, with potentially significant savings in computational time.

This article builds on previous relevant reviews (Candel 2002, Dowling & Morgans 2005, Candel et al. 2014, Poinsot 2017, Juniper & Sujith 2018) by focusing on the flow physics, tools, and advances associated with moving predictive capability of thermoacoustic instability toward increasingly realistic combustors, as well as advances that may allow mitigation of thermoacoustic instability to be incorporated into new designs.

The behavior of acoustic waves within a combustor is dictated by its geometry, boundary conditions, and temperature profile. Section 2 explores the different categories of geometry used in practical combustors, along with their associated acoustic characteristics. This review focuses on geometries relevant to gas turbine applications, but the key flow physics and interaction mechanisms also apply to other applications. Section 3 then discusses the effect of the burner, in terms of both the response of the flame's unsteady heat release rate and the burner's acoustic characteristics. Combustor acoustic modes depend on combustor boundary conditions, while the thermoacoustic stability is determined by the balance between acoustic energy gain and acoustic energy damping. Section 4 discusses combustor boundaries and flow field in terms of acoustic boundary conditions, temperature profile, and acoustic damping. For acoustic damping, sources both inherent to the combustion system and deliberately introduced through acoustic dampers are considered. An important aspect of work in the field over the last decade has been the success of hybrid/coupled approaches for predicting thermoacoustic instability. Section 5 presents examples in which thermoacoustic instability has been successfully predicted using both direct computational tools and hybrid/coupled tools employing a range of different approaches.

2. COMBUSTOR GEOMETRY

The combustor geometry informs the length scales and timescales over which acoustic waves propagate and reflect back from boundaries to interact with the flame. Together with the combustor boundary conditions and speed of sound field, it informs the frequency and acoustic mode shape corresponding to any thermoacoustic instability.

Combustors sustain a mean flow, and the pressure fluctuations associated with their acoustic waves generally remain small compared to the mean pressure, even during large-amplitude thermoacoustic oscillations. Furthermore, the effect of viscosity on the acoustic waves is generally negligible. Small (linear) flow perturbations are then governed by the linearized Euler equations (Dowling & Stow 2003), which can be solved numerically, either as part of a full flow field computational fluid dynamics (CFD) solution or as a separate linearized simulation. If some further simplifications are made, it is possible to solve for the acoustic field more quickly but still with good accuracy and potentially in a manner that retains more physical insight. There are two main branches of approach for further acoustic simplifications.

The first is to neglect the effect of the mean flow on the acoustic field, yielding an inhomogeneous wave equation (Dowling & Stow 2003):

$$\frac{1}{\bar{c}^2} \frac{\partial^2 p'}{\partial t^2} - \bar{\rho} \nabla \cdot \left(\frac{1}{\bar{\rho}} \nabla p' \right) = \frac{(\gamma - 1)}{\bar{c}^2} \frac{\partial q'}{\partial t}, \quad 1.$$

where $\bar{c}$ and $\bar{\rho}$ denote the speed of sound and density in an undisturbed medium, p' denotes the pressure fluctuation, q' the heat release rate fluctuation per unit volume, and γ the ratio of specific heats. This can be converted to a Helmholtz equation in the frequency domain and solved numerically using Helmholtz solvers. The response of the flame's unsteady heat release rate to acoustic perturbations is needed for closure and is normally included as a flame model, provided from models, CFD, or experiments, as discussed in Section 3. This Helmholtz solver approach to simplifying the acoustics has the advantage of being able to account for spatially complex geometries and speed of sound fields. However, an implication of neglecting the mean flow is that many physical sources of acoustic damping are not incorporated, so an artificial acoustic damping term is typically added to the left-hand side to attempt to correct for this.

The second approach is to retain the mean flow contribution. The mean flow not only causes a shift in the acoustic mode frequencies of the order of the Mach number squared, such that the error in neglecting it at $M = 0.2$ is approximately 5% (Dowling & Stow 2003), but is also fundamental to capturing the transport of entropy, vorticity, and compositional fluctuations as well as the main acoustic damping mechanisms. The simplification this time exploits the fact that thermoacoustic instability tends to occur at low frequencies—this being because flames are generally more sensitive to low-frequency disturbances and the dominant acoustic damping mechanisms increase with frequency. This means that thermoacoustic modes typically correspond to the low-order acoustic modes of the combustion system, which exhibit a reduced spatial dimension. The reduced spatial dimension underpins low-order network approaches, which retain the contribution of the mean flow but instead simplify the geometry and mean speed of sound field. The low frequencies also imply that the spatial extent of the flame is short compared to the long acoustic wavelengths, allowing the generation of acoustics arising from the flame's unsteady heat release rate to be simplified. This can be included either through the combination of a flame model and flame jump conditions or through a combined burner transfer matrix approach, as discussed in Section 3.

Several broad categories of combustor geometry as used in gas turbine applications are shown in **Figure 1**, with these geometry types and their key flow physics also extending to other applications. They include (a) single-can combustors with one or multiple burners; (b) can-annular combustors, in which many can combustors are interconnected through an annular gap at their outlet; and (c) annular combustors, in which both the plenum and the combustor are annular in shape and many burners are installed around the combustor circumference. The geometric simplifications and their implications for the acoustic fields in each of these combustor geometry types are discussed in more detail in the following sections.

2.1. Can Combustors

For a typical single-can combustor, its longitudinal length significantly exceeds its length across the other two dimensions, as shown in **Figure 1a**. For frequencies below the cut-on frequency of transverse/radial acoustic modes, only planar acoustic waves can propagate: Higher-order modes are evanescent and decay exponentially. This means that away from sources of the heat release rate, the acoustic field is governed by the one-dimensional convected wave equation (Dowling & Stow 2003),

$$\frac{1}{\bar{c}^2} \frac{\bar{D}^2 p'}{Dt^2} - \frac{\partial^2 p'}{\partial x^2} = 0, \quad 2.$$

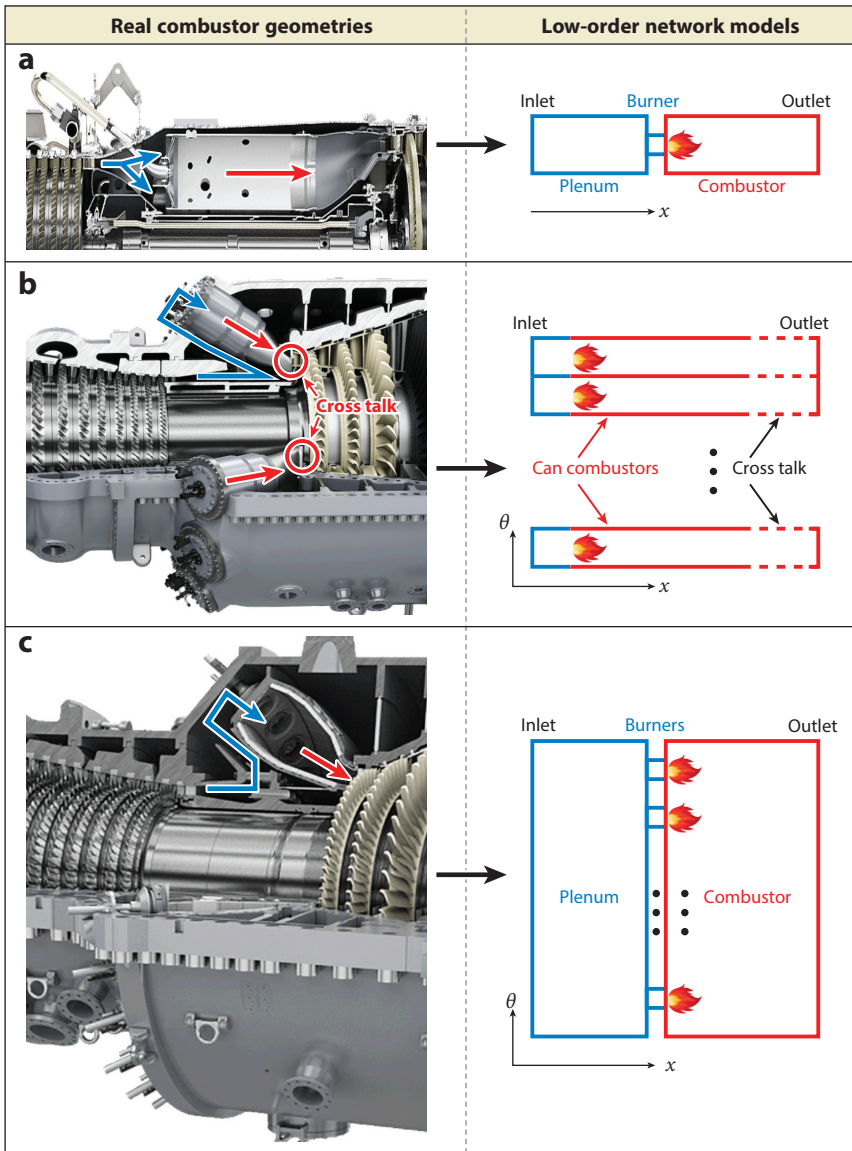


Figure 1

Three categories of combustor geometry and their corresponding low-order network model representations, showing pictures of (a) SGT-A05 (single-can), (b) SGT5-9000HL (can-annular), and (c) SGT5-4000F (annular) combustors. Images provided by Siemens Energy.

where $\bar{D}/Dt = \partial/\partial t + \bar{u}\partial/\partial x$ is the convective derivative and $\bar{u}$ is the one-dimensional approximation to the mean flow velocity. The solution for this consists of planar waves propagating in either direction, at the speed of sound with respect to the mean flow. Acoustic feedback inside the combustor establishes through only these planar acoustic waves, and the thermoacoustic mode shapes vary only in the longitudinal direction (a mode shape with purely longitudinal variation is shown in **Figure 2a**, but for an annular geometry).

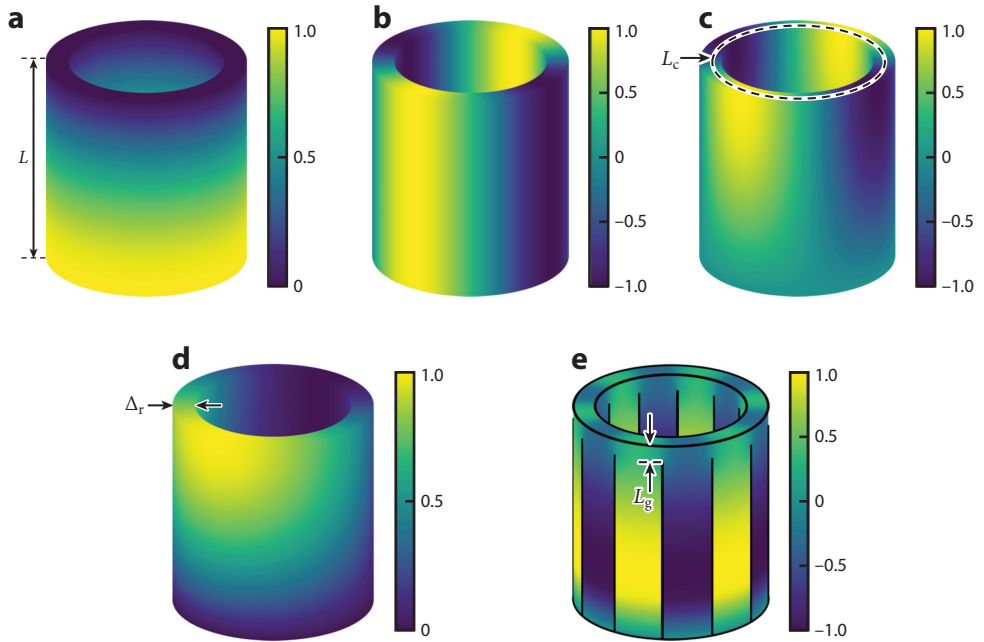


Figure 2

Examples of acoustic pressure mode shapes corresponding to (a) a purely longitudinal mode, (b) a purely circumferential mode, (c) a mixed longitudinal-circumferential mode, (d) a slanted mode, and (e) a push-pull mode in a simplified representation of a can-annular combustor with 12 cans. The longitudinal direction is taken as upward. L denotes the longitudinal length of the combustor, L_c and Δ_r the mean circumference and the radial gap width of the annular combustor respectively, and L_g the length of the annular gap at the outlets of the can-annular combustor. The color bars denote normalized pressure perturbation.

To incorporate the effect of the flame, it can usually be assumed that the longitudinal extent of the flame is much shorter than the dominant acoustic wavelengths. This means that the change in acoustic wave strengths across the flame can be taken to be spatially discontinuous. It can be included either by the combined effect of a flame model and compact jump conditions for first-order (linear) flow fluctuations across the flame or by using a combined burner transfer matrix approach, as described in Section 3.

It is worth mentioning that another modeling approach, employing truncated Galerkin expansions (Culick & Yang 1995), can be used to model the acoustics. Such approaches account for neither the mean flow nor the velocity jump across the flame, and errors may arise if truncation is applied after too few terms (Dowling & Stow 2003). However, they extend more naturally to nonlinear acoustic regimes and hence are useful where this can be important, e.g., for rocket engines (Culick & Yang 1995).

Even though the presence of flame unsteadiness can significantly affect the stability of thermoacoustic modes, it usually modifies the acoustic mode shape and frequency only slightly. Thus, as long as the combustor length, mean temperature distribution, and acoustic boundary conditions (which are discussed in more detail in Section 4) can be prescribed, the frequencies of the possible thermoacoustic modes follow quite straightforwardly. However, predicting the stability of a mode, as well as its oscillation amplitude if it is unstable, requires the flame response and the acoustic damping to be prescribed; these are usually much more challenging and will be addressed in Sections 3 and 4, respectively.

It is possible for more than one thermoacoustic mode to be unstable, although a single mode is generally seen to dominate the thermoacoustic oscillations resulting from instability (Stow & Dowling 2009, Li & Morgans 2015, Acharya et al. 2018, John et al. 2023). If the transverse dimensions of the combustor are large enough and the acoustic damping not sufficiently strong, transverse thermoacoustic instabilities can occur, as is often the case in rocket engines (Culick & Yang 1995, Urbano et al. 2016), afterburners (Rogers & Marble 1956, Nakaya et al. 2021), and sometimes gas turbine combustors (Schwing et al. 2011, Berger et al. 2017). Recent interest has emerged in the use of sequential combustors for their operational flexibility and ultralow NOx emissions: They employ a secondary flame downstream of the main flame to shorten the high temperature region. For these, thermoacoustic interactions remain similar, with the heat release rate from both the main and the secondary flame zones contributing (Schulz et al. 2019, Xiong et al. 2021, Choi & Kim 2023).

2.2. Can-Annular Combustors

Many modern heavy-duty gas turbines have a can-annular geometry. Multiple separate can combustors are installed around a circumference, with a transition duct at the combustor outlets linking to the relevant segment of the annular turbine inlet, as shown in **Figure 1b**.

Due to thermal expansion effects, a gap is usually left between the transition duct outlet and the turbine inlet guide vane. This leads to acoustic cross talk between neighboring can combustors. Even though the flame in each can is well separated from those in other cans, this cross talk can result in acoustically coupled thermoacoustic modes. An example is the push-pull thermoacoustic mode, where the pressure oscillations between neighboring cans are out of phase (Farisco et al. 2017, Moon et al. 2019), as illustrated in **Figure 2e**, where the cross-talk gap is denoted L_g . Several recent studies have investigated the acoustic characteristics of the cross talk, for example, modeling it using Rayleigh conductivity-based hole models (von Saldern et al. 2021b), considering the acoustically quasi-one-dimensional end annulus (Haeringer et al. 2021), and taking the effect of mean gazing flow into consideration (Orchini 2022). The cross talk gives rise to both longitudinal and circumferential modes, with clusters of modes very close in frequency occurring (Ghirardo et al. 2019). Accounting for the nonlinear responses of the flames, these clusters may cause complex and relatively slow mode interaction transients, with different modes able to synchronize (von Saldern et al. 2021a).

When the system exhibits rotational symmetry, i.e., all combustors are identical, Bloch-wave theory can be used to provide the boundary condition at the cross talk of a single can (Ghirardo et al. 2019), reducing the system to be analyzed to just a single can. If a source of asymmetry between cans is introduced, the full system needs to be analyzed. Such asymmetry can arise from one can having a different flame response, different equivalence ratio (Moon et al. 2021), different nozzle swirl distribution (Guan et al. 2023), or different can-to-can coupling strength (Buschmann et al. 2023). A significant impact on the azimuthal pressure distribution can result (Ghirardo et al. 2019).

2.3. Annular Combustors

Combustors with a thin annular shape are widely used in both aeroengines and land-based gas turbines. Typically, more than 10–20 burners are uniformly installed around the annulus, with the aim of achieving a uniform temperature distribution at the turbine inlet, as shown in **Figure 1c**. The combustor's mean circumference (denoted L_c in the simplified geometries of **Figure 2**) is typically much larger than its thin radial gap (denoted Δ_r in **Figure 2**), while its length (denoted L in **Figure 2**) can vary from being much shorter to being of the same order as the circumference.

At low frequencies, thermoacoustic modes that involve acoustic propagation purely in the circumferential (also termed azimuthal) direction can exist if both the inlet and outlet boundaries are acoustically closed. A mode shape with purely circumferential variation is illustrated in **Figure 2b**. For such modes, if the combustor is further acoustically decoupled from the plenum, simple models based on the Galerkin expansion can be used (Noiray et al. 2011, Ghirardo et al. 2016). When the combustor and plenum acoustics are coupled, a quasi-one-dimensional linear model that accounts for purely circumferential acoustic propagation (Bauerheim et al. 2014a, 2016) can offer analytical expressions for mode stability and azimuthal mode degeneracy/splitting properties, accounting for both uniform and differing burners around the annulus (Bauerheim et al. 2014b, Poinso 2017).

When the combustor's longitudinal length is not negligible compared to the acoustic wavelength or the acoustic boundary conditions differ from closed–closed, acoustic waves can vary in the longitudinal as well as circumferential direction. Research on annular combustor geometries has benefited from the development of lab-scale annular combustion rigs over the last decade (Worth & Dawson 2013, Bourgoin et al. 2015b). The combination of longitudinal and circumferential variations may lead to acoustic mode shapes that vary only in the longitudinal direction, as shown in **Figure 2a**, mode shapes that vary in both the circumferential and longitudinal directions, as shown in **Figure 2c**, and even modes that involve a coupling between circumferential and longitudinal components (Bourgoin et al. 2015a, Moeck et al. 2019, Orchini et al. 2019, Yang et al. 2019a), as shown in **Figure 2d**. The presence of acoustic dampers or varying burners around the annulus will lead to more complicated modal couplings. Two-dimensional low-order network models (Stow & Dowling 2001, Evesque & Polifke 2002, Stow & Dowling 2009, Yang et al. 2019a), which apply wave solutions to the convected wave equation in a thin annulus and allow for variations in both the longitudinal and circumferential directions (Dowling & Stow 2003), can be used to capture these effects. Such models have been used to study the effect of dampers (Stow & Dowling 2003, Yang et al. 2019b) and feedback control (Morgans & Stow 2007, Illingworth & Morgans 2010) in annular combustors and have included the effects of differing burners around the annulus (Morgans & Stow 2007) and flame nonlinearities (Stow & Dowling 2004, 2009; Yang et al. 2019a). The effect of symmetry breaking resulting from differing burners can lead to mode splitting of circumferential modes (Noiray et al. 2011, Bauerheim et al. 2014b).

Circumferential modes differ from other modes in that rather than having acoustic boundary conditions at either end of their spatial domain, they instead have the requirement of periodicity every 2π radians. This permits both standing and spinning modes, with the balance of these determined by a parameter known as the nature angle (Ghirardo & Bothien 2018, Ghirardo et al. 2021). When the system is rotationally symmetric, such as when the burners are all the same and a purely spinning mode is considered, Bloch-wave theory can be used to reduce the simulation of the full annular combustor to a single segment (Mensah et al. 2016). An azimuthal mean flow, even if small, causes a difference in the clockwise and anticlockwise wave propagation speeds and thus significantly affects the nature angle (Bauerheim et al. 2015). The flame response to azimuthal velocity perturbations can be nonzero for asymmetric flames, arising, for example, from a non-negligible azimuthal mean flow. While the azimuthal flame response may be much smaller than its longitudinal counterpart, it may also alter the nature angle (Li et al. 2019). Recent experimental results (Nygård et al. 2021) showed that an annular geometry with swirling flames generally gives different flame responses to clockwise and anticlockwise acoustic forcing. This leads to the heat release rate perturbation having a different nature angle to that of the pressure perturbation and a nonzero heat release rate response at the pressure node of a perfectly standing pressure mode.

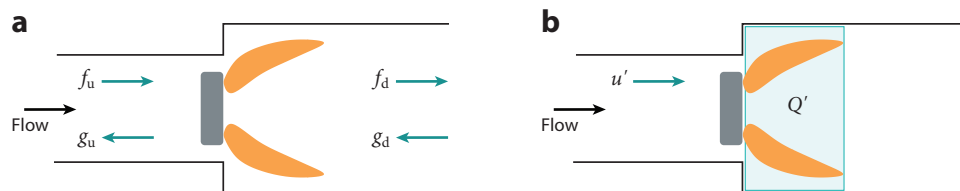


Figure 3

The two main approaches for accounting for the unsteady heat release rate of the flame. (a) The burner transfer matrix approach (Section 3.1), where f and g denote the pressure amplitudes of waves moving to the right and left, respectively. (b) The flame model approach (Section 3.2), where u' denotes the velocity fluctuation just upstream of the flame and Q' denotes the unsteady component of the flame's global heat release rate.

3. BURNER GEOMETRY

Thermoacoustic instabilities depend not only on the propagation and reflection of acoustic waves in the combustor, but also on how the flame generates and responds to acoustic waves. It is at the burner (also referred to as an injector) that reactants are brought together, setting up conditions for combustion within a desired spatial zone in the combustor. Burners are typically located at the upstream end of the combustor (with sequential/staged combustors involving further sequences of burners along the combustor). Their effect on thermoacoustic behavior occurs through both the unsteady characteristics of the flame(s) associated with them and their acoustic characteristics. These can be treated either in a combined manner or separately, as follows.

3.1. Combined Acoustic/Unsteady Flame Treatment of Burners

The combined effect of burner geometry and the effect of its subsequent unsteady flame on the acoustics can be characterized through a burner transfer matrix, which relates acoustic wave strengths upstream and downstream of the burner. Following the pressure wave notation of **Figure 3a**, the burner transfer matrix $[T]_{2 \times 2}$ is defined as

$$\begin{bmatrix} f_d \\ g_d \end{bmatrix} = [T]_{2 \times 2} \begin{bmatrix} f_u \\ g_u \end{bmatrix}. \quad 3.$$

This can be measured experimentally using acoustic excitation (e.g., from a loudspeaker) and pressure sensors both upstream and downstream of the burner unit (Paschereit et al. 2002). The approach can be applied to all burner geometry types but is limited to linear analysis and prediction of linear stability.

For nonlinear analysis, including prediction of limit cycle oscillations [particularly for the many situations where nonlinearity is associated with the flame rather than the acoustics (Noiray et al. 2008)], or for combustors where upstream and downstream acoustic excitation becomes difficult, it may be preferable to treat the acoustics of the burner and the subsequent unsteady response of its flame separately.

3.2. Unsteady Flame Response of Burners

The response of the flame's global unsteady heat release rate to acoustic perturbations can be characterized by what is widely known as the flame model (Candel 2002, Lieuwen 2003). As shown in **Figure 3b**, this typically links the velocity perturbation ahead of the flame to the global heat release rate perturbation of the flame, although it can be extended to also include the effect of equivalence ratio fluctuations on the heat release rate (Lieuwen 2003).

Many early thermoacoustic studies were based on analytical characterization of this flame model, most famously through the n - τ model (Crocco 1951), which takes the flame model to be a gain, n , and a time delay, τ . Semi-analytical approaches have also been used, for example, via kinematic tracking of a thin, fast-reacting flame front (Fleifil et al. 1996); these offer important insights but tend not to capture sufficient complexity for real combustors. For these, it is preferable to characterize the flame response to acoustic perturbations using experiments or CFD, in the form of a linear flame transfer function (FTF) (Giauque et al. 2005, Kim et al. 2010), a weakly nonlinear flame describing function (FDF) (Balachandran et al. 2005, Noiray et al. 2008, Palies et al. 2011, Han & Morgans 2015, Xia et al. 2019), or (linear) distributed time delays (Polifke 2020). Following the notation of **Figure 3b**, the FTF and FDF are defined as

$$\text{FTF} = \frac{\hat{Q}(\omega)/\bar{Q}}{\hat{u}(\omega)/\bar{u}}, \quad \text{FDF} = \frac{\hat{Q}(\omega, |\hat{u}|)/\bar{Q}}{\hat{u}(\omega, |\hat{u}|)/\bar{u}}, \quad 4.$$

where ω is the radian frequency, $\hat{(\cdot)}$ denotes the Fourier amplitude, and $\bar{(\cdot)}$ denotes the mean value. It can be seen that the FDF incorporates weak nonlinearity: It assumes that the main heat release rate response matches the frequency of the velocity forcing but with a gain and phase shift that depend upon the forcing amplitude as well as frequency. Only by using nonlinear flame models such as the FDF is it possible to predict the final thermoacoustic oscillations resulting from instability (Stow & Dowling 2009, Han et al. 2015, Laera et al. 2017a).

Flame models typically have the form of a low-pass filter combined with a phase lag. The latter is linked to time delays with various physical roots: acoustic inertia (flames respond to hydrodynamic/vortical disturbances resulting from acoustic excitation, which advect along the flame front), mixing, transport, and sometimes evaporation delays (Candel 2002, Ducruix et al. 2003). While it is possible to define the FTF and FDF with respect to a range of different acoustic variables (Gaudron et al. 2017), it is the upstream velocity perturbation that links most physically to these effects. Interestingly, hydrogen enrichment of the fuel has been found to extend the bandwidth of the flame response—the gain drop-off is pushed to higher frequencies (Æsøy et al. 2021, Lim et al. 2021). This may at least partly explain why hydrogen-fueled combustors often exhibit an increased propensity to thermoacoustic instability (Beita et al. 2021).

Swirl burners often exhibit additional dips in the gain of their flame response at certain frequencies (Candel et al. 2014, Æsøy et al. 2022). There are currently relatively few data on flame models for multiflame burners (Noiray et al. 2008); these hold promise for achieving stable low NO_x combustion of 100% hydrogen and so may receive increased attention in the future.

3.3. Acoustic Characteristics of Burners

Combustor thermoacoustic behavior can sometimes be decoupled from that of upstream components such as the plenum (Schuller et al. 2012). Then the location of the burner outlet, i.e., where the reactants leave the burner and enter the combustion chamber, can be taken to form the thermoacoustic domain's upstream acoustic boundary, with this being characterized by the flow contraction presented by the burner flow passageways. Most simplistically, this may be approximated as a closed acoustic boundary, but more sophisticated treatments are possible.

If the combustor is not sufficiently decoupled from components upstream of the burner, which in general comprise both the airstream and the fuel stream, then the upstream boundary will need to shift upstream of these (Stow & Dowling 2001, 2009; Han et al. 2015; Laera et al. 2017a; Xia et al. 2019). As the acoustic impedance of the airstream is typically much lower than that of the fuel stream, often only the former is accounted for, via components such as air plenums. The acoustic characteristics of the burner must be prescribed, with the simplest approach being to account

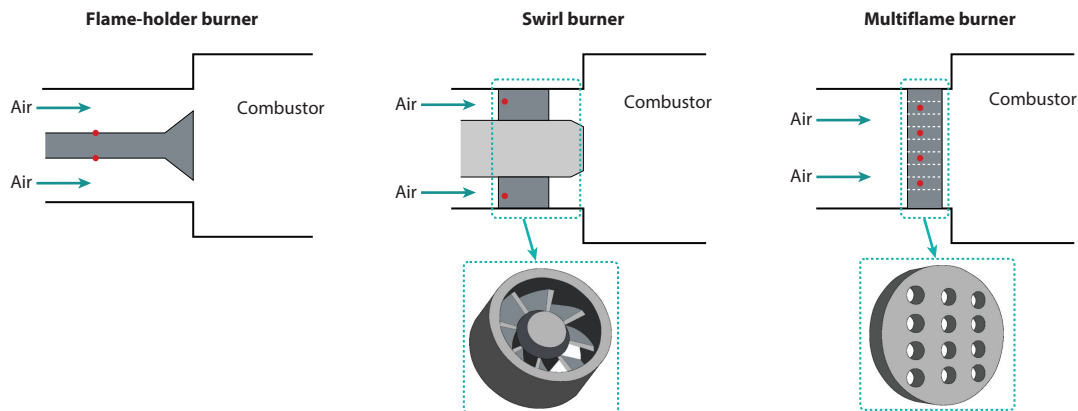


Figure 4

Simplified illustration of the three broad categories of burner geometry for fluid reactants. The red dots denote the approximate locations of fuel injection.

for the compact flow contraction at the burner inlet, the longitudinal variation of acoustic waves within the burner, and the compact expansion at the burner outlet, but to neglect all details of the burner beyond this (Stow & Dowling 2001, 2009; Han et al. 2015; Laera et al. 2017a). Models for the flow expansion can account for the stagnation pressure loss that occurs due to large-scale flow separation, as is discussed further in Section 4.4.

The effect of the flame's heat release rate on the acoustic wave strengths can be captured by assuming the flame length to be acoustically compact and applying one-dimensional quasi-steady linearized flow conservation equations across it, with the heat release rate included in the energy equation. These manifest as jump conditions across the flame (Dowling 1997, Dowling & Stow 2003), i.e., across the shaded zone in **Figure 3b**. In addition to changing the strength of acoustic waves, the flame unsteadiness can lead to the generation of entropy perturbations that advect downstream from the flame—this effect is also captured in the above jump conditions (Dowling & Stow 2003).

More complex models for the acoustic characteristics of the burner require some details of the burner geometry to be considered. For fluid reactants, burners can be broadly categorized into (a) flame-holder-type burners, (b) swirl burners, and (c) multiflame burners, as illustrated in **Figure 4**. Incorporating the details of the burner geometry remains at an early stage but offers promise for better capturing and potentially exploiting the associated acoustic damping. Relevant progress for the different burner types is briefly outlined below.

3.3.1. Flame-holder burners. Flame-holder burners typically stabilize the flame via a recirculation zone generated by a bluff body. Such a bluff body will inevitably introduce drag, with the potential to affect the acoustic characteristics. Dowling (1995) showed analytically that bluff-body drag was likely to be thermoacoustically important above area blockage ratios of 25%. The acoustic response of a simple bluff body—a circular disc surrounded by flow through an annular aperture—was then considered in more detail by Schleicher & Howe (2013), who used an unsteady drag term to account for the acoustic damping associated with vortex shedding from the disc edge. Su et al. (2021) considered a circular bluff-body burner centrally located at the expansion plane of a circular duct: Using a Green's function and a vortex sheet model, they predicted the acoustic reflection and transmission characteristics well compared to results from nonreacting compressible large eddy simulations (LES).

3.3.2. Swirl burners. Swirl burners with multiple swirl passages (Candel et al. 2014) are ubiquitous in gas turbine combustors. Despite this, there have been few attempts to model their acoustic response beyond applying compact area changes. Su et al. (2019) simplified the geometry of a swirler passage, with acoustic predictions comparing well to CFD. Their results confirmed that the length of the passage affects the phase of the acoustic response and that acoustic energy is mainly dissipated by the unsteady vorticity shed from the swirl vanes and the large-scale flow expansion at the passage exit.

3.3.3. Multi flame burners. Multi flame burners (Durox et al. 2009) are plates with multiple small holes; a flame front forms downstream of each hole. These multiple flame fronts may interact. For such burners, models for the acoustic response of isolated holes with mean flow passing through them—based on the work of Howe (1979)—can capture acoustic damping due to vortex shedding. More recent work has found that short holes, where the mean flow that separates upon entering the hole does not reattach within the hole (typically holes with a length less than 1.5 times their diameter), can generate rather than damp acoustic energy (Jing & Sun 2000, Su et al. 2015). Models that account for two-way acoustic–vorticity coupling can capture this (Yang & Morgans 2016, 2017b), with some studies also linking to a purely hydrodynamic instability (Fabre et al. 2020). For longer holes, accounting for the unsteady vortex sheets shed from the hole inlet and outlet properly captures the acoustic response (Brokof et al. 2023). For multihole plates, interaction between neighboring holes can affect the hole acoustics—particularly the reactance, i.e., the imaginary part of the impedance (Lee et al. 2007).

Although linking the aeroacoustic response of multi flame burner holes with thermoacoustic stability is still in its infancy, it is a concept that may gain importance. The rapidly growing interest in hydrogen as a fuel means that multi flame burners (which offer both flashback resistance in the context of hydrogen’s fast flame speed and fast mixing of products for low NO_x) may be used more widely in the future (Beita et al. 2021).

4. COMBUSTOR BOUNDARIES AND FLOW FIELD

As discussed in Section 2, the thermoacoustic modes of a system depend upon the combustor geometry and the acoustic boundary conditions. The thermoacoustic stability is then determined by the balance between (a) the acoustic energy source arising from the unsteady heat release rate of the flame and (b) the damping rate of the acoustic energy (Chu 1965, Dowling & Morgans 2005). This balance is important both in determining the system’s linear stability and in determining the nonlinear oscillation amplitude resulting from instability, the latter of which occurs when the above acoustic energy source and acoustic energy damping terms are balanced.

The boundaries and flow field of a combustor affect both its acoustic boundary conditions and its acoustic damping. The acoustic damping may arise from the intrinsic properties of the geometry and flow field (including the burner itself, as discussed in Section 3). It may also be augmented by the addition of acoustic dampers as passive control methods for mitigating thermoacoustic instability (Richards et al. 2006, Zhao & Li 2015, Lahiri & Bake 2017). It is worth noting that since damping typically arises from acoustic–flow interactions, it is often naturally accounted for in low-order network models (Gaudron et al. 2021), but it needs to be more carefully included in Helmholtz solvers (Ni et al. 2017, 2018; Heilmann & Sattelmayer 2022), which by default neglect mean flow effects.

4.1. Upstream Boundary

Combustion chambers in real engines typically sit between the compressor and turbine, with the thermoacoustic domain boundary conditions set by these components. As discussed in Section 3,

the combustor can sometimes be decoupled thermoacoustically from components upstream of the burner (Schuller et al. 2012), such that the burner outlet can be taken as the thermoacoustic domain's upstream boundary. The acoustic boundary condition then needs to capture the flow contraction (as seen from downstream) presented by the burner flow passageways, with the various options described in Section 3. When the thermoacoustic domain needs to extend upstream of the burner, the upstream boundary condition of the compressor is often approximated as choked (Dowling & Stow 2003). In cases where the domain is truncated between the compressor and the burner outlet, it can be hard to choose how far upstream this should extend (Wolf et al. 2012).

4.2. Downstream Boundary

Lab-based combustors operating at atmospheric pressure typically have open downstream boundaries, but combustors operating at raised pressure have more complex downstreams, for example, a nozzle that may or may not be choked. For gas turbines, the downstream end of the combustor interfaces with the turbine, the first stator row of which is known as the nozzle guide vane (NGV). The flow through this rapidly accelerates to an approximately choked condition, turning as it does so. Acoustically, the reflection of acoustic waves is no longer the only source of boundary acoustics, as the indirect noise (Marble & Candel 1977) arising from the acceleration of entropy, compositional, and possibly vortical fluctuations may also need accounting for (Goh & Morgans 2013, Duran et al. 2014, Dowling & Mahmoudi 2015, Morgans & Duran 2016, Ihme 2017).

The downstream acoustic boundary condition can be approximated by analytical methods that assume choked nozzle flows and account for both direct and indirect acoustic reflection. Such models have progressed from those assuming one-dimensional, very low-frequency perturbations (Marble & Candel 1977) to those that extend to any frequency (Duran & Moreau 2013, Magri et al. 2016, Yeddula et al. 2022), including for annular configurations (Duran & Morgans 2015). Analytical attempts to account for blade effects (Cumpsty & Marble 1977, Mishra & Bodony 2013, Guzmán-Iñigo et al. 2021) exist, but approaches that push beyond the zero frequency assumption remain immature for practical application. Experiments (Bake et al. 2009) and computations (Leyko et al. 2009, Brouzet et al. 2024) can be used to inform nozzle flow boundary conditions as well as real blade passage (NGV) boundary conditions (Leyko et al. 2014).

4.3. Combustor Walls

The combustor bounding walls can affect both the flame and the acoustic waves in the combustor. The mean and unsteady flame response can be affected by wall heat transfer and wall temperature effects near the flame anchoring position (Agostinelli et al. 2021). For the acoustics, visco-thermal damping effects at walls are generally negligible for the typical cross-sectional size of real combustors (Li & Morgans 2016). The effect on the acoustics of heat transfer and an axially varying temperature field is discussed in Section 4.5, and the effect of dampers embedded into or attached to the combustor walls in Section 4.6.

4.4. Area Changes

Although the main combustion chamber often exhibits only gradual changes in the cross-sectional area, the larger thermoacoustic domain, comprising the plenum, burner, combustor, etc., typically involves a sequence of rapid area changes. When such area changes happen over a length scale that is much smaller than the acoustic wavelength, jump conditions can be used to link the strength of linear flow perturbations across this change. For area contractions, the flow changes are isentropic, and conservation of mass and energy combined with the isentropic condition yields jump

conditions (Dowling & Stow 2003). These jump conditions also apply to axisymmetric nonplanar entropy waves passing through a flow contraction (Yang et al. 2022).

At rapid area expansions, large-scale flow separation occurs and the isentropic condition must be replaced by a condition that captures the key effect of this flow separation and stagnation pressure loss. This condition involves a momentum balance that assumes that the static pressure is unchanged across the area expansion interface (Ronneberger 1987, Dowling & Stow 2003). In a recent study, Gaudron et al. (2023) confirmed the validity of this assumption for flow perturbations as well as the mean flow, by comparing to simulations using the linearized Navier–Stokes equations. The authors furthermore characterized the acoustic damping associated with the stagnation pressure loss, finding that the flow expansion damps acoustic energy, except for a very few conditions involving a large Mach number when acoustic generation is possible. This implies that acoustic modeling approaches that assume constant static pressure across an area expansion implicitly account for an important source of acoustic damping.

While entropy noise is typically more relevant for flow contractions where the flow accelerates, recent laboratory experiments on entropy noise (Rolland et al. 2017) have used a downstream orifice plate, which first contracts and then expands the flow. For the flow expansion, the compact isentropic model (Marble & Candel 1977) failed to accurately predict the entropy noise. Modeling by Yang et al. (2020) showed that the spatial extent of the recirculation zone caused by flow separation was the main cause of this divergence. By applying the aforementioned assumption of constant static pressure across the area change, entropy noise can be predicted well (Guzmán-Iñigo et al. 2022).

4.5. Spatially Varying Flow Field

In real combustors, the flow field temperature and possibly the cross-sectional area often vary in the axial direction, the former due to mixing with cooling flows and/or heat losses. Flow field temperature changes directly alter the speed of sound and hence affect acoustic propagation and thermoacoustic modes. Acoustic modeling approaches based on the inhomogeneous Helmholtz equation are able to account for axial variations in temperature and cross-sectional area naturally (Laera et al. 2017a). Acoustic characterization via wave-based models can account for these effects simplistically by slicing the combustor domain into smaller axial segments (Laera et al. 2017b). There has also been significant recent progress in extending wave-based acoustic modeling (i.e., for low-order acoustic network models) to account for axial variations in temperature (Li & Morgans 2017, Li et al. 2018), cross-sectional area (Yeddula & Morgans 2021), and heat transfer (Yeddula et al. 2022), including for annular geometries (Li et al. 2021).

4.6. Acoustic Dampers

The types of acoustic damper commonly added to combustion systems include Helmholtz resonators, perforated liners, and quarter-wave tubes (Richards et al. 2006, Zhao & Li 2015, Lahiri & Bake 2017). These are all underpinned by holes sustaining a bias and/or grazing flow in order to absorb acoustic energy. Vorticity generated by flow separation at the hole edges is convected by the mean flow and finally dissipated into heat, absorbing the acoustic energy. Linear acoustic models are usually sufficient to predict the acoustic characteristics of such dampers (Eldredge & Dowling 2003, Bellucci et al. 2004, Dupere & Dowling 2005). For holes where the dominant flow is the bias flow through them rather than grazing flow, vortex-sound theory for thin circular holes (Howe 1979) has been widely used to predict the acoustic characteristics, predicting acoustic absorption/damping across all frequencies. However, for holes with similar length and diameter, the flow that separates from the hole inlet edge does not reattach before the hole exit, and the hole

can generate acoustic energy rather than absorbing it over some frequencies (Jing & Sun 2000, Su et al. 2015). Recent semianalytical models suggest that this is caused by coupling between vortex shedding at the inlet edge and its interaction with the outlet edge at the expansion (Yang & Morgans 2016, 2017b). Such holes exhibit strong sensitivity of their acoustic characteristics to slight modifications in the hole edge geometry (Guzmán-Iñigo et al. 2019), which has recently led to successful geometry optimization for acoustic damping (Guzmán-Iñigo & Morgans 2024). Longer holes, with a length-to-diameter ratio of $1.5 \sim 3$, exhibit vortex shedding at both the inlet and outlet edges, and the growth and decay of unsteady vorticity inside the hole significantly affect the hole's absorption characteristics (Brokof et al. 2023).

For dampers installed in realistic combustors, it can be important to account for more complex effects, such as grazing flow (Sun et al. 2002, Eldredge & Dowling 2003, Moers et al. 2017), temperature differences across the damper (Yang & Morgans 2017a, Miniero et al. 2023) (since the bias flow through dampers often also provides cooling), and, for annular geometries, the interplay with spinning and standing modes (Stow & Dowling 2003, Lepers et al. 2005, Camporeale et al. 2008, Bothien et al. 2014, Zahn et al. 2017, Yang et al. 2019b, Zhang et al. 2020).

5. EXAMPLES OF THERMOACOUSTIC INSTABILITY PREDICTION FOR REALISTIC COMBUSTORS

The prediction of thermoacoustic instabilities in realistic combustors has progressed over the last two decades, targeting different levels of combustor and burner complexity and using different prediction tools. The targeted combustor type varies from lab-scale single-burner combustors to industrial-scale multiple-burner annular combustors, with the burners varying from bluff-body stabilized burners through laboratory matrix burners to industrial swirl burners. The prediction methods can be broken down into two main categories: (a) direct methods, which use CFD, mainly in the form of compressible LES, to solve for thermoacoustic oscillations in a combustion system, and (b) hybrid/coupled methods, which couple separate treatments for the acoustic waves and the flame unsteadiness. The computational expense of hybrid/coupled methods is generally much lower than for direct methods, since the physics-informed characterization of the acoustic waves is captured with fewer resources. Some examples of thermoacoustic predictions achieved and a summary of the combustor type and prediction method are shown in **Table 1**.

For single-burner combustors, predicting the thermoacoustic mode frequencies requires resolving the acoustic propagation within the spatial domain along with the acoustic boundary conditions at either end. The former is relatively straightforward, requiring knowledge of the mean temperature and thus speed of sound; the latter can be obvious for some combustors but commonly requires some consideration of the acoustic-flow interactions at the boundaries. In order to go beyond predicting thermoacoustic modal frequencies to predicting the stability of these modes, the linear flame response and the acoustic damping must be characterized with reasonable accuracy. While it is possible to prescribe the linear flame response using theoretical or numerical models, for realistic combustors it usually needs to be obtained from experimental measurements or LES. The need for experimental or CFD characterization is especially true if the flame is long enough to not be acoustically compact or is at elevated pressure. Due to the typical low combustor Mach numbers, LES for the flame response can be incompressible, i.e., allowing density changes due to temperature but not pressure—this exploits the fact that flames respond primarily to the hydrodynamic fluctuations initiated by acoustic excitation (Candel 2002, Ducruix et al. 2003). Incompressible LES has the benefit of allowing larger time steps and avoiding the need to deal with the acoustic performance of the simulation's boundary conditions.

Table 1 Summary of predictions for thermoacoustic instabilities

Reference	Combustor type	Method	Prediction	Validation
Stow & Dowling 2001	Ind/annular	LONM + FTF	Freq	Exp
Evesque & Polifke 2002	Model annular	LONM + BTM	Freq	HS
Schuermans et al. 2003	Longitudinal/annular	Galerkin (SS) + BTM	Freq	HS
Stow & Dowling 2004	Ind/annular	LONM + FDF	Freq/type/amp	Exp
Kopitz et al. 2005	Lab/annular	LONM + FTF	Freq	Exp
Nicoud et al. 2007	Ind/annular	HS + FTF	Freq/type	No
Staffelbach et al. 2009	Ind/swirl/annular	Compressible LES	Freq/amp	No
Stow & Dowling 2009	Ind/annular	LONM (time domain)	Type	Exp
Wolf et al. 2012	Ind/swirl/annular	Compressible LES	Freq/amp	No
Silva et al. 2013	Lab/swirl/can	HS + exp FDF	Freq/amp	Exp
Campa & Camporeale 2014	Ind/annular	HS + CFD mean flow	Freq	No
Han et al. 2015	Lab/bluff-body/can	LONM + LES FDF	Freq/amp	Exp
Mensah et al. 2016	Ind/annular	HS + BWT + FTF	Freq	HS
Urbano et al. 2016	Ind/liquid rocket	Compressible LES	Triggering/freq	Exp
Laera et al. 2017a	Lab/M-B/annular	HS + exp FDF	Freq/amp	Exp
Laera et al. 2017b	Lab/M-B/annular	LONM + exp FDF	Freq/type/amp	Exp
Li et al. 2017	Lab/long flame/can	LONM + LES FDF	Freq/amp	Exp
Xia et al. 2019	Ind/pd/swirl/can	LONM + LES FDF	Freq/amp	Exp
Yang et al. 2019a	Lab/M-B/annular	LONM + FDF	Freq/type/amp	HS
Fredrich et al. 2021	Lab/swirl/can	Compressible LES	Freq/amp	Exp
Kumar et al. 2023	Lab/swirl/can	Compressible LES	Freq/amp	Exp

Abbreviations: amp, mode amplitude; BTM, burner transfer matrix; BWT, Bloch-wave theory; CFD, computational fluid dynamics; exp, experiment; FDF, flame describing function; freq, mode frequency; FTF, flame transfer function; HS, Helmholtz solver; ind, industrial scale; lab, lab scale; LES, large eddy simulation; LONM, low-order network model; M-B, matrix burner; pd, pressurized; SS, state space; type, mode type.

Capturing the amplitude of the thermoacoustic oscillations resulting from instability is more challenging, again requiring both the nonlinear flame response and the acoustic damping to be prescribed with reasonable accuracy.

Progress in achieving computational prediction of thermoacoustic instability using direct computational approaches was reviewed by Poinot (2017), with subsequent works shown in **Table 1**. Achieving fast and accurate computational prediction using coupled/hybrid methods had been a long-standing challenge, but progress combining low-order network models for the acoustics with incompressible LES for the flame has been made over the last decade for both lab-scale (Han et al. 2015, Li et al. 2017) and industrial-complexity (Xia et al. 2019) can combustors. For the latter, the pressurized combustion rig for which good thermoacoustic instability and oscillation predictions were achieved is shown in **Figure 5a**, with its low-order thermoacoustic network representation shown in **Figure 5b**. The coupled/hybrid method was able to correctly predict that the combustor operating at 3-bar pressure was stable, while at 6-bar pressure it was unstable, with the final frequency and amplitude of the resulting oscillations predicted well.

Annular combustors, beyond the challenges discussed above, require acoustic propagation to be characterized in both the longitudinal and circumferential directions. Accurate prediction may also need coupling between circumferential modes of different orders to be accounted for, as well as the ability to determine whether modes are spinning, standing, mixed, slanted, or involve even more complicated coupling (Laera et al. 2017b, Prieur et al. 2017, Yang et al. 2019a). In terms

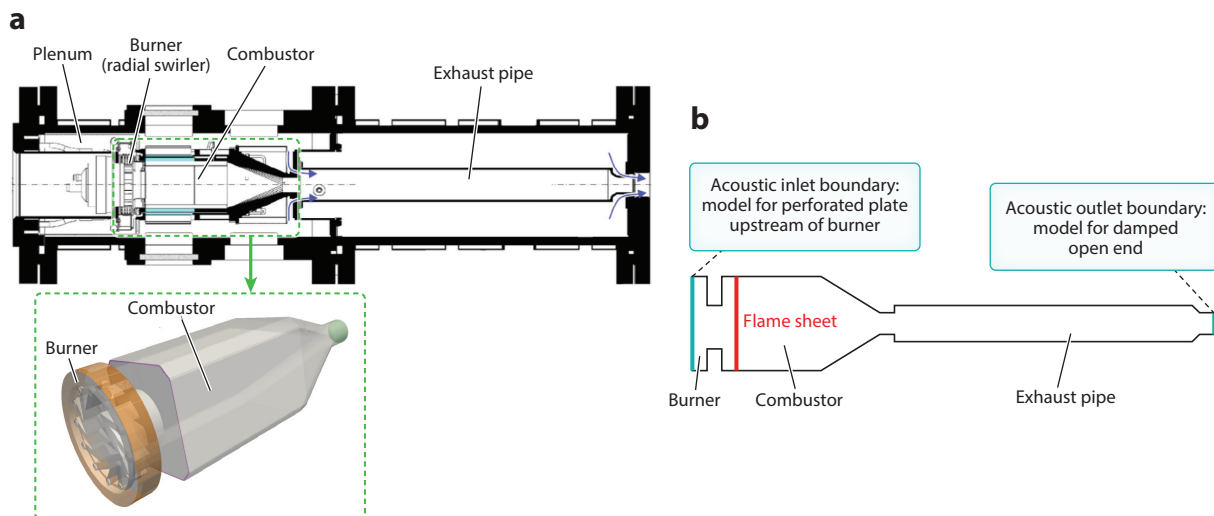


Figure 5

The pressurized (3 bar and 6 bar) industrial demonstrator rig (Stopper et al. 2013) for which good hybrid/coupled thermoacoustic predictions were achieved (Xia et al. 2019). (a) Schematic of the rig, burner, and combustor. (b) Sketch of low-order thermoacoustic network representation. Top portion of panel *a* adapted with permission from Xia (2019). Bottom portion of panel *a* adapted from Xia et al. (2018) (CC BY 4.0).

of predicting thermoacoustic instability in annular combustors, notable progress was made by Laera et al. (2017a), who combined a Helmholtz solver with experimentally measured FDFs and predicted the frequency and amplitude of both spinning and standing limit cycles observed in an experimental lab annular combustor.

For combustors that exhibit more complex flow physics, such as real gas effects in supercritical rocket engines, accurate prediction requires further refined simulations (Urbano et al. 2016). For such combustors, as well as for when the final thermoacoustic behavior is more complex than limit cycle oscillations (Kumar et al. 2023), experimentally validated predictions have so far been limited to direct computational approaches.

Finally, it is notable that none of the entries in **Table 1** are for can-annular combustor geometries. While there have been several lab-based experimental rigs developed for annular combustors (Worth & Dawson 2013, Bourgouin et al. 2015b), comparable facilities for can-annular systems remain needed.

SUMMARY POINTS

1. Thermoacoustic instabilities are caused by a two-way coupling between acoustic waves and unsteady heat release rate.
2. Thermoacoustic instabilities are problematic for combustors in aeroengines, land-based gas turbines, rocket engines, domestic boilers, etc., often arising late in the design and development process.
3. There has been significant research activity over the last decade on modeling and understanding thermoacoustic instabilities in annular-shaped combustors, largely driven

by new experimental facilities. There is now growing research activity on modeling and understanding thermoacoustic instabilities in can-annular geometries.

4. Fast and accurate computational prediction of thermoacoustic instability and thermoacoustic oscillations in real combustors remains challenging and computationally intensive, largely due to the range of length scales, timescales, and flow physics at play.
5. Significant progress has been made over the last decade using coupled/hybrid approaches for computational prediction of thermoacoustic instability. Such approaches combine separate computational treatments for the acoustic waves and the flame. Successful predictions extend to pressurized and industrially representative combustors.

FUTURE ISSUES

1. The move to decarbonize energy systems and aviation is driving a transition to new fuels. Some of these will require substantial redesign of the burner and/or combustor. This transition will likely bring new thermoacoustic instability problems but also new opportunities to explore ways of mitigating thermoacoustic instability.
2. Can-annular combustor geometries are relevant to large/efficient gas turbines for energy generation. Further thermoacoustic characterization and understanding of these are needed across experimental, modeling, and numerical tools.
3. Given that burner designs are likely to undergo quite significant changes in the context of the transition to new fuels, it will be important to quickly develop an understanding of both the unsteady flame response and acoustic damping mechanisms associated with new burner designs.
4. Further understanding and accurate incorporation of the main acoustic damping mechanisms into thermoacoustic instability prediction methods are needed.
5. Data-driven tools such as optimization remain relatively unexplored for mitigation of thermoacoustic instability and may offer avenues for exploiting the high sensitivity that thermoacoustic stability can exhibit to design changes.

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LITERATURE CITED

Acharya VS, Bothien MR, Lieuwen TC. 2018. Non-linear dynamics of thermoacoustic eigen-mode interactions. *Combust. Flame* 194:309–21

- Æsøy E, Aguilar JG, Bothien MR, Worth NA, Dawson JR. 2021. Acoustic-convective interference in transfer functions of methane/hydrogen and pure hydrogen flames. *J. Eng. Gas Turbines Power* 143(12):121017
- Æsøy E, Nygård HT, Worth NA, Dawson JR. 2022. Tailoring the gain and phase of the flame transfer function through targeted convective-acoustic interference. *Combust. Flame* 236:111813
- Agostinelli P, Laera D, Boxx I, Gicquel L, Poinso T. 2021. Impact of wall heat transfer in large eddy simulation of flame dynamics in a swirled combustion chamber. *Combust. Flame* 234:111728
- Bake F, Richter C, Mühlbauer B, Kings N, Röhle I, et al. 2009. The entropy wave generator (EWG): a reference case on entropy noise. *J. Sound Vib.* 326(3–5):574–98
- Balachandran R, Ayoola B, Kaminski C, Dowling AP, Mastorakos E. 2005. Experimental investigation of the nonlinear response of turbulent premixed flames to imposed inlet velocity oscillations. *Combust. Flame* 143(1–2):37–55
- Bauerheim M, Cazalens M, Poinso T. 2015. A theoretical study of mean azimuthal flow and asymmetry effects on thermo-acoustic modes in annular combustors. *Proc. Combust. Inst.* 35(3):3219–27
- Bauerheim M, Nicoud F, Poinso T. 2016. Progress in analytical methods to predict and control azimuthal combustion instability modes in annular chambers. *Phys. Fluids* 28(2):021303
- Bauerheim M, Parmentier JF, Salas P, Nicoud F, Poinso T. 2014a. An analytical model for azimuthal thermoacoustic modes in an annular chamber fed by an annular plenum. *Combust. Flame* 161(5):1374–89
- Bauerheim M, Salas P, Nicoud F, Poinso T. 2014b. Symmetry breaking of azimuthal thermo-acoustic modes in annular cavities: a theoretical study. *J. Fluid Mech.* 760:431–65
- Beita J, Talibi M, Sadasivuni S, Balachandran R. 2021. Thermoacoustic instability considerations for high hydrogen combustion in lean premixed gas turbine combustors: a review. *Hydrogen* 2(1):33–57
- Bellucci V, Flohr P, Paschereit CO, Magni F. 2004. On the use of Helmholtz resonators for damping acoustic pulsations in industrial gas turbines. *J. Eng. Gas Turbines Power* 126(2):271–75
- Berger FM, Hummel T, Hertweck M, Kaufmann J, Schuermans B, Sattelmayer T. 2017. High-frequency thermoacoustic modulation mechanisms in swirl-stabilized gas turbine combustors—part I: experimental investigation of local flame response. *J. Eng. Gas Turbines Power* 139(7):071501
- Bothien MR, Noiray N, Schuermans B. 2014. A novel damping device for broadband attenuation of low-frequency combustion pulsations in gas turbines. *J. Eng. Gas Turbines Power* 136(4):041504
- Bourgouin JF, Durox D, Moeck JP, Schuller T, Candel S. 2015a. A new pattern of instability observed in an annular combustor: the slanted mode. *Proc. Combust. Inst.* 35(3):3237–44
- Bourgouin JF, Durox D, Moeck JP, Schuller T, Candel S. 2015b. Characterization and modeling of a spinning thermoacoustic instability in an annular combustor equipped with multiple matrix injectors. *J. Eng. Gas Turbines Power* 137(2):021503
- Brokof P, Guzmán-Iñigo J, Yang D, Morgans AS. 2023. The acoustics of short circular holes with reattached bias flow. *J. Sound Vib.* 546:117435
- Brouzet D, Krisna B, McCormick D, Reimann CA, Mendoza J, Ihme M. 2024. Analysis of direct and indirect noise in a next-generation aviation gas turbine combustor. *Combust. Flame* 260:113249
- Buschmann PE, Worth NA, Moeck JP. 2023. Thermoacoustic oscillations in a can-annular model combustor with asymmetries in the can-to-can coupling. *Proc. Combust. Inst.* 39(4):5707–15
- Campa G, Camporeale SM. 2014. Prediction of the thermoacoustic combustion instabilities in practical annular combustors. *J. Eng. Gas Turbines Power* 136(9):091504
- Camporeale SM, Fortunato B, Mastrovito M. 2008. Prediction of thermoacoustic instability in combustion chamber equipped with passive dampers. In *Proceedings of the ASME Turbo Expo 2008: Power for Land, Sea, and Air*, Vol. 3: *Combustion, Fuels and Emissions, Parts A and B*, pp. 1087–94. New York: Am. Soc. Mech. Eng.
- Candel S. 2002. Combustion dynamics and control: progress and challenges. *Proc. Comb. Inst.* 29:1–28
- Candel S, Durox D, Schuller T, Bourgouin JF, Moeck JP. 2014. Dynamics of swirling flames. *Annu. Rev. Fluid Mech.* 46:147–73
- Choi Y, Kim KT. 2023. Mode shape-dependent thermoacoustic interactions between a lean-premixed primary flame and an axially-staged transverse reacting jet. *Combust. Flame* 255:112884
- Chu BT. 1965. On the energy transfer to small disturbances in fluid flow (Part I). *Acta Mech.* 1(3):215–34
- Crocco L. 1951. Aspects of combustion stability in liquid propellant rocket motors Part I: Fundamentals. Low frequency instability with monopropellants. *J. Am. Rocket Soc.* 21(6):163–78

- Culick FE, Yang V. 1995. Overview of combustion instabilities in liquid-propellant rocket engines. In *Liquid Rocket Engine Combustion Instability*, ed. V Yang, pp. 3–37. Washington, DC: Am. Inst. Aeronaut. Astrophys.
- Cumpsty N, Marble F. 1977. The interaction of entropy fluctuations with turbine blade rows; a mechanism of turbojet engine noise. *Proc. R. Soc. A* 357(1690):323–44
- Dowling AP. 1995. The calculation of thermoacoustic oscillations. *J. Sound Vib.* 180(4):557–81
- Dowling AP. 1997. Nonlinear self-excited oscillations of a ducted flame. *J. Fluid Mech.* 346:271–90
- Dowling AP, Mahmoudi Y. 2015. Combustion noise. *Proc. Combust. Inst.* 35:65–100
- Dowling AP, Morgans AS. 2005. Feedback control of combustion oscillations. *Annu. Rev. Fluid Mech.* 37:151–82
- Dowling AP, Stow SR. 2003. Acoustic analysis of gas turbine combustors. *J. Propul. Power* 19(5):751–64
- Ducruix S, Schuller T, Durox D, Candel S. 2003. Combustion dynamics and instabilities: elementary coupling and driving mechanisms. *J. Propul. Power* 19(5):722–34
- Dupere ID, Dowling AP. 2005. The use of Helmholtz resonators in a practical combustor. *J. Eng. Gas Turbines Power* 127(2):268–75
- Duran I, Moreau S. 2013. Solution of the quasi-one-dimensional linearized Euler equations using flow invariants and the Magnus expansion. *J. Fluid Mech.* 723:190–231
- Duran I, Moreau S, Nicoud F, Livebardon T, Bouty E, Poinot T. 2014. Combustion noise in modern aero-engines. *Aerosp. Lab* 7:5
- Duran I, Morgans AS. 2015. On the reflection and transmission of circumferential waves through nozzles. *J. Fluid Mech.* 773:137–53
- Durox D, Schuller T, Noiray N, Birbaud AL, Candel S. 2009. Rayleigh criterion and acoustic energy balance in unconfined self-sustained oscillating flames. *Combust. Flame* 156(1):106–19
- Eldredge JD, Dowling AP. 2003. The absorption of axial acoustic waves by a perforated liner with bias flow. *J. Fluid Mech.* 485:307–35
- Emmert T, Bomberg S, Polifke W. 2015. Intrinsic thermoacoustic instability of premixed flames. *Combust. Flame* 162(1):75–85
- Evesque S, Polifke W. 2002. Low-order acoustic modelling for annular combustors: validation and inclusion of modal coupling. In *Proceedings of the ASME Turbo Expo 2002: Power for Land, Sea, and Air*, Vol. 1: *Turbo Expo 2002*, pp. 321–31. New York: Am. Soc. Mech. Eng.
- Fabre D, Longobardi R, Citro V, Luchini P. 2020. Acoustic impedance and hydrodynamic instability of the flow through a circular aperture in a thick plate. *J. Fluid Mech.* 885:A11
- Farisco F, Panek L, Kok JB. 2017. Thermo-acoustic cross-talk between cans in a can-annular combustor. *Int. J. Spray Combust. Dyn.* 9(4):452–69
- Fleifil M, Annaswamy AM, Ghoneim Z, Ghoniem AF. 1996. Response of a laminar premixed flame to flow oscillations: a kinematic model and thermoacoustic instability results. *Combust. Flame* 106(4):487–510
- Fredrich D, Jones WP, Marquis AJ. 2021. Thermo-acoustic instabilities in the PRECCINSTA combustor investigated using a compressible LES-pdf approach. *Flow Turbul. Combust.* 106:1399–415
- Gaudron R, Gatti M, Mirat C, Schuller T. 2017. Impact of the injector size on the transfer functions of premixed laminar conical flames. *Combust. Flame* 179:138–53
- Gaudron R, Guzmán Iñigo J, Morgans AS. 2023. Variation of acoustic energy across sudden area expansions sustaining a subsonic flow. *ALAA J.* 61(1):378–90
- Gaudron R, Yang D, Morgans A. 2021. Acoustic energy balance during the onset, growth, and saturation of thermoacoustic instabilities. *J. Eng. Gas Turbines Power* 143(4):041026
- Ghirardo G, Bothien MR. 2018. Quaternion structure of azimuthal instabilities. *Phys. Rev. Fluids* 3(11):113202
- Ghirardo G, Di Giovine C, Moeck JP, Bothien MR. 2019. Thermoacoustics of can-annular combustors. *J. Eng. Gas Turbines Power* 141(1):011007
- Ghirardo G, Juniper M, Moeck JP. 2016. Weakly nonlinear analysis of thermoacoustic instabilities in annular combustors. *J. Fluid Mech.* 805:52–87
- Ghirardo G, Nygård HT, Cuquel A, Worth NA. 2021. Symmetry breaking modelling for azimuthal combustion dynamics. *Proc. Combust. Inst.* 38(4):5953–62
- Giauque A, Selle L, Gicquel L, Poinot T, Buechner H, et al. 2005. System identification of a large-scale swirled partially premixed combustor using LES and measurements. *J. Turbul.* (6):N21

- Goh CS, Morgans AS. 2013. The influence of entropy waves on the thermoacoustic stability of a model combustor. *Combust. Sci. Technol.* 185:249–68
- Guan Y, Li LK, Jegal H, Kim KT. 2023. Effect of flame response asymmetries on the modal patterns and collective states of a can-annular lean-premixed combustion system. *Proc. Combust. Inst.* 39(4):4731–39
- Guzmán-Iñigo J, Durán I, Morgans AS. 2021. Scattering of entropy waves into sound by isolated aerofoils. *J. Fluid Mech.* 923:A10
- Guzmán-Iñigo J, Morgans AS. 2024. Designing the edges of holes (with bias flow) to maximise acoustic damping. *J. Sound Vib.* 575:118224
- Guzmán-Iñigo J, Yang D, Gaudron R, Morgans AS. 2022. On the scattering of entropy waves at sudden area expansions. *J. Sound Vib.* 540:117261
- Guzmán-Iñigo J, Yang D, Johnson HG, Morgans AS. 2019. Sensitivity of the acoustics of short circular holes with bias flow to inlet edge geometries. *ALAA J.* 57(11):4835–44
- Haeringer M, Fournier GJ, Meindl M, Polifke W. 2021. A strategy to tune acoustic terminations of single-can test-rigs to mimic thermoacoustic behavior of a full engine. *J. Eng. Gas Turbines Power* 143(7):071029
- Han X, Li J, Morgans AS. 2015. Prediction of combustion instability limit cycle oscillations by combining flame describing function simulations with a thermoacoustic network model. *Combust. Flame* 162(10):3632–47
- Han X, Morgans AS. 2015. Simulation of the flame describing function of a turbulent premixed flame using an open-source LES solver. *Combust. Flame* 162(5):1778–92
- Heilmann G, Sattelmayer T. 2022. On the convective wave equation for the investigation of combustor stability using FEM-methods. *Int. J. Spray Combust. Dyn.* 14(1–2):55–71
- Hoeijmakers M, Kornilov V, Arteaga IL, de Goey P, Nijmeijer H. 2014. Intrinsic instability of flame–acoustic coupling. *Combust. Flame* 161(11):2860–67
- Howe M. 1979. On the theory of unsteady high Reynolds number flow through a circular aperture. *Proc. R. Soc. A* 366(1725):205–23
- Ihme M. 2017. Combustion and engine-core noise. *Annu. Rev. Fluid Mech.* 49:277–310
- Illingworth SJ, Morgans AS. 2010. Adaptive feedback control of combustion instability in annular combustors. *Combust. Sci. Technol.* 182(2):143–64
- Jing X, Sun X. 2000. Effect of plate thickness on impedance of perforated plates with bias flow. *ALAA J.* 38(9):1573–78
- John T, Acharya VS, Bothien MR, Lieuwen TC. 2023. Dynamics of coupled thermoacoustic modes: noise and frequency spacing effects. *Combust. Flame* 252:112738
- Juniper MP, Sujith RI. 2018. Sensitivity and nonlinearity of thermoacoustic oscillations. *Annu. Rev. Fluid Mech.* 50:661–89
- Kim D, Lee JG, Quay BD, Santavica DA, Kim K, Srinivasan S. 2010. Effect of flame structure on the flame transfer function in a premixed gas turbine combustor. *J. Eng. Gas Turbines Power* 132(2):021502
- Kopitz J, Huber A, Sattelmayer T, Polifke W. 2005. Thermoacoustic stability analysis of an annular combustion chamber with acoustic low order modeling and validation against experiment. In *Proceedings of the ASME Turbo Expo 2005: Power for Land, Sea, and Air*, Vol. 2: *Turbo Expo 2005*, pp. 583–93. New York: Am. Soc. Mech. Eng.
- Kumar AD, Massey JC, Stöhr M, Meier W, Swaminathan N. 2023. Period-2 thermoacoustics in a swirl-stabilised partially premixed flame computed using large eddy simulation. *Flow Turbul. Combust.* 111(3):995–1028
- Laera D, Schuller T, Prieur K, Durox D, Camporeale SM, Candel S. 2017a. Flame describing function analysis of spinning and standing modes in an annular combustor and comparison with experiments. *Combust. Flame* 184:136–52
- Laera D, Yang D, Li J, Morgans AS. 2017b. *A novel acoustic network model to study the influence of mean flow and axial temperature distribution on spinning limit cycles in annular combustors*. Paper presented at 23rd AIAA/CEAS Aeroacoustics Conference, Denver, CO, AIAA Pap. 2017-3191
- Lahiri C, Bake F. 2017. A review of bias flow liners for acoustic damping in gas turbine combustors. *J. Sound Vib.* 400:564–605
- Lee SH, Ih JG, Peat KS. 2007. A model of acoustic impedance of perforated plates with bias flow considering the interaction effect. *J. Sound Vib.* 303(3–5):741–52

- Lepers J, Krebs W, Prade B, Flohr P, Pollarolo G, Ferrante A. 2005. Investigation of thermoacoustic stability limits of an annular gas turbine combustor test-rig with and without Helmholtz-resonators. In *Proceedings of the ASME Turbo Expo 2005: Power for Land, Sea, and Air*, Vol. 2: *Turbo Expo 2005*, pp. 177–89. New York: Am. Soc. Mech. Eng.
- Leyko M, Duran I, Moreau S, Nicoud F, Poinso T. 2014. Simulation and modelling of the waves transmission and generation in a stator blade row in a combustion-noise framework. *J. Sound Vib.* 333(23):6090–106
- Leyko M, Nicoud F, Poinso T. 2009. Comparison of direct and indirect combustion noise mechanisms in a model combustor. *ALAA J.* 47(11):2709–16
- Li C, Yang D, Li S, Zhu M. 2019. An analytical study of the effect of flame response to simultaneous axial and transverse perturbations on azimuthal thermoacoustic modes in annular combustors. *Proc. Combust. Inst.* 37(4):5279–87
- Li J, Morgans AS. 2015. Time domain simulations of nonlinear thermoacoustic behaviour in a simple combustor using a wave-based approach. *J. Sound Vib.* 346:345–60
- Li J, Morgans AS. 2016. Feedback control of combustion instabilities from within limit cycle oscillations using H_∞ loop-shaping and the v -gap metric. *Proc. R. Soc. A* 472(2191):20150821
- Li J, Morgans AS. 2017. The one-dimensional acoustic field in a duct with arbitrary mean axial temperature gradient and mean flow. *J. Sound Vib.* 400:248–69
- Li J, Wang D, Morgans AS, Yang L. 2021. Analytical solutions of acoustic field in annular combustion chambers with non-uniform cross-sectional surface area and mean flow. *J. Sound Vib.* 506:116175
- Li J, Xia Y, Morgans AS, Han X. 2017. Numerical prediction of combustion instability limit cycle oscillations for a combustor with a long flame. *Combust. Flame* 185:28–43
- Li J, Yang D, Morgans AS. 2018. The effect of an axial mean temperature gradient on communication between one-dimensional acoustic and entropy waves. *Int. J. Spray Combust. Dyn.* 10(2):131–53
- Lieuwen T. 2003. Modeling premixed combustion-acoustic wave interactions: a review. *J. Propuls. Power* 19:765–81
- Lim Z, Li J, Morgans AS. 2021. The effect of hydrogen enrichment on the forced response of $\text{CH}_4/\text{H}_2/\text{Air}$ laminar flames. *Int. J. Hydrogen Energy* 46(46):23943–53
- Magri L, O'Brien J, Ihme M. 2016. Compositional inhomogeneities as a source of indirect combustion noise. *J. Fluid Mech.* 799:R4
- Marble FE, Candel SM. 1977. Acoustic disturbance from gas non-uniformities convected through a nozzle. *J. Sound Vib.* 55:225–43
- Mensah GA, Campa G, Moeck JP. 2016. Efficient computation of thermoacoustic modes in industrial annular combustion chambers based on Bloch-wave theory. *J. Eng. Gas Turbines Power* 138(8):081502
- Miniero L, Mensah GA, Bourquard C, Noiray N. 2023. Failure of thermoacoustic instability control due to periodic hot gas ingestion in Helmholtz dampers. *J. Sound Vib.* 548:117544
- Mishra A, Bodony DJ. 2013. Evaluation of actuator disk theory for predicting indirect combustion noise. *J. Sound Vib.* 332(4):821–38
- Moeck JP, Durox D, Schuller T, Candel S. 2019. Nonlinear thermoacoustic mode synchronization in annular combustors. *Proc. Combust. Inst.* 37(4):5343–50
- Moers E, Tonon D, Hirschberg A. 2017. Strouhal number dependency of the aero-acoustic response of wall perforations under combined grazing-bias flow. *J. Sound Vib.* 389:292–308
- Mongia HC, Held T, Hsiao G, Pandalai R. 2003. Challenges and progress in controlling dynamics in gas turbine combustors. *J. Propul. Power* 19(5):822–29
- Moon K, Jegal H, Gu J, Kim KT. 2019. Combustion-acoustic interactions through cross-talk area between adjacent model gas turbine combustors. *Combust. Flame* 202:405–16
- Moon K, Yoon C, Kim KT. 2021. Influence of rotational asymmetry on thermoacoustic instabilities in a can-annular lean-premixed combustor. *Combust. Flame* 223:295–306
- Morgans AS, Duran I. 2016. Entropy noise: a review of theory, progress and challenges. *Int. J. Spray Combust.* 8(4):285–98
- Morgans AS, Stow SR. 2007. Model-based control of combustion instabilities in annular combustors. *Combust. Flame* 150(4):380–99
- Nakaya S, Omi K, Okamoto T, Ikeda Y, Zhao C, et al. 2021. Instability and mode transition analysis of a hydrogen-rich combustion in a model afterburner. *Proc. Combust. Inst.* 38(4):5933–42

- Ni F, Miguel-Brebion M, Nicoud F, Poinso T. 2017. Accounting for acoustic damping in a Helmholtz solver. *AIAA J.* 55(4):1205–20
- Ni F, Nicoud F, Méry Y, Staffelbach G. 2018. Including flow–acoustic interactions in the Helmholtz computations of industrial combustors. *AIAA J.* 56(12):4815–29
- Nicoud F, Benoit L, Sensiau C, Poinso T. 2007. Acoustic modes in combustors with complex impedances and multidimensional active flames. *AIAA J.* 45(2):426–41
- Noiray N, Bothien MR, Schuermans B. 2011. Investigation of azimuthal staging concepts in annular gas turbines. *Combust. Theory Model.* 15(5):585–606
- Noiray N, Durox D, Schuller T, Candel S. 2008. A unified framework for nonlinear combustion instability analysis based on the flame describing function. *J. Fluid Mech.* 615:139–67
- Nygård HT, Ghirardo G, Worth NA. 2021. Azimuthal flame response and symmetry breaking in a forced annular combustor. *Combust. Flame* 233:111565
- Oefelein JC, Yang V. 1993. Comprehensive review of liquid-propellant combustion instabilities in F-1 engines. *J. Propul. Power* 9(5):657–77
- Orchini A. 2022. An effective impedance for modelling the aeroacoustic coupling of ducts connected via apertures. *J. Sound Vib.* 520:116622
- Orchini A, Mensah GA, Moeck JP. 2019. Effects of nonlinear modal interactions on the thermoacoustic stability of annular combustors. *J. Eng. Gas Turbines Power* 141(2):021002
- Palies P, Durox D, Schuller T, Candel S. 2011. Nonlinear combustion instability analysis based on the flame describing function applied to turbulent premixed swirling flames. *Combust. Flame* 158(10):1980–91
- Paschereit CO, Schuermans B, Polifke W, Mattson O. 2002. Measurement of transfer matrices and source terms of premixed flames. *J. Eng. Gas Turbines Power* 124(2):239–47
- Poinso T. 2017. Prediction and control of combustion instabilities in real engines. *Proc. Combust. Inst.* 36(1):1–28
- Polifke W. 2020. Modeling and analysis of premixed flame dynamics by means of distributed time delays. *Prog. Energy Combust. Sci.* 79:100845
- Prieur K, Durox D, Schuller T, Candel S. 2017. A hysteresis phenomenon leading to spinning or standing azimuthal instabilities in an annular combustor. *Combust. Flame* 175:283–91
- Richards GA, Straub DL, Robey EH. 2005. Passive control of combustion instabilities in stationary gas turbines. In *Combustion Instabilities in Gas Turbine Engines*, ed. TC Lieuwen, V Yang, pp. 533–79. Reston, VA: Am. Inst. Aeronaut. Astronaut.
- Rogers DE, Marble FE. 1956. A mechanism for high-frequency oscillation in ramjet combustors and afterburners. *J. Jet Propul.* 26(6):456–62
- Rolland E, De Domenico F, Hochgreb S. 2017. Theory and application of reverberated direct and indirect noise. *J. Fluid Mech.* 819:435–64
- Ronneberger D. 1987. *Theoretische und experimentelle Untersuchung der Schallausbreitung durch Querschnittssprünge und Lochplatten in Strömungskanälen*. Tech. Rep., DFG-Abschlussbericht, Drittes Phys. Inst. Univ. Göttingen, Göttingen, Ger.
- Schleicher RM, Howe MS. 2013. On the interaction of sound with an annular aperture in a mean flow duct. *J. Sound Vib.* 332(21):5594–605
- Schuermans B, Bellucci V, Paschereit CO. 2003. Thermoacoustic modeling and control of multi burner combustion systems. In *Proceedings of the ASME Turbo Expo 2003, collocated with the 2003 International Joint Power Generation Conference*, Vol. 2: *Turbo Expo 2003*, pp. 509–19. New York: Am. Soc. Mech. Eng.
- Schuller T, Durox D, Palies P, Candel S. 2012. Acoustic decoupling of longitudinal modes in generic combustion systems. *Combust. Flame* 159(5):1921–31
- Schulz O, Doll U, Ebi D, Droujko J, Bourquard C, Noiray N. 2019. Thermoacoustic instability in a sequential combustor: large eddy simulation and experiments. *Proc. Combust. Inst.* 37(4):5325–32
- Schwing J, Sattelmayer T, Noiray N. 2011. Interaction of vortex shedding and transverse high-frequency pressure oscillations in a tubular combustion chamber. In *Proceedings of the ASME 2011 Turbo Expo: Turbine Technical Conference and Exposition*, Vol. 2: *Combustion, Fuels and Emissions, Parts A and B*, pp. 259–68. New York: Am. Soc. Mech. Eng.
- Silva CF. 2023. Intrinsic thermoacoustic instabilities. *Prog. Energy Combust. Sci.* 95:101065

- Silva CF, Nicoud F, Schuller T, Durox D, Candel S. 2013. Combining a Helmholtz solver with the flame describing function to assess combustion instability in a premixed swirled combustor. *Combust. Flame* 160(9):1743–54
- Staffelbach G, Gicquel L, Boudier G, Poinot T. 2009. Large eddy simulation of self excited azimuthal modes in annular combustors. *Proc. Combust. Inst.* 32(2):2909–16
- Stopper U, Meier W, Sadanandan R, Stöhr M, Aigner M, Bulat G. 2013. Experimental study of industrial gas turbine flames including quantification of pressure influence on flow field, fuel/air premixing and flame shape. *Combust. Flame* 160(10):2103–18
- Stow SR, Dowling AP. 2001. Thermoacoustic oscillations in an annular combustor. In *Proceedings of the ASME Turbo Expo 2001: Power for Land, Sea, and Air*, Vol. 2: *Coal, Biomass and Alternative Fuels; Combustion and Fuels; Oil and Gas Applications; Cycle Innovations*, V002T02A004. New York: Am. Soc. Mech. Eng.
- Stow SR, Dowling AP. 2003. Modelling of circumferential modal coupling due to Helmholtz resonators. In *Proceedings of the ASME Turbo Expo 2003, collocated with the 2003 International Joint Power Generation Conference*, Vol. 2: *Turbo Expo 2003*, pp. 129–37. New York: Am. Soc. Mech. Eng.
- Stow SR, Dowling AP. 2004. Low-order modelling of thermoacoustic limit cycles. In *Proceedings of the ASME Turbo Expo 2004: Power for Land, Sea, and Air*, Vol. 1: *Turbo Expo 2004*, pp. 775–86. New York: Am. Soc. Mech. Eng.
- Stow SR, Dowling AP. 2009. A time-domain network model for nonlinear thermoacoustic oscillations. *J. Eng. Gas Turbines Power* 131(3):031502
- Su J, Garmory A, Carrotte J. 2019. On the acoustic response of a generic gas turbine fuel injector passage. *J. Sound Vib.* 446:343–73
- Su J, Rupp J, Garmory A, Carrotte JF. 2015. Measurements and computational fluid dynamics predictions of the acoustic impedance of orifices. *J. Sound Vib.* 352:174–91
- Su J, Yang D, Morgans AS. 2021. Modelling of sound-vortex interaction for the flow through an annular aperture. *J. Sound Vib.* 509:116250
- Sun X, Jing X, Zhang H, Shi Y. 2002. Effect of grazing–bias flow interaction on acoustic impedance of perforated plates. *J. Sound Vib.* 254(3):557–73
- Urbano A, Selle L, Staffelbach G, Cuenot B, Schmitt T, et al. 2016. Exploration of combustion instability triggering using large eddy simulation of a multiple injector liquid rocket engine. *Combust. Flame* 169:129–40
- von Saldern JG, Moeck JP, Orchini A. 2021a. Nonlinear interaction between clustered unstable thermoacoustic modes in can-annular combustors. *Proc. Combust. Inst.* 38(4):6145–53
- von Saldern JG, Orchini A, Moeck JP. 2021b. Analysis of thermoacoustic modes in can-annular combustors using effective Bloch-type boundary conditions. *J. Eng. Gas Turbines Power* 143(7):071019
- Wolf P, Staffelbach G, Gicquel LY, Müller JD, Poinot T. 2012. Acoustic and large eddy simulation studies of azimuthal modes in annular combustion chambers. *Combust. Flame* 159(11):3398–413
- Worth NA, Dawson JR. 2013. Modal dynamics of self-excited azimuthal instabilities in an annular combustion chamber. *Combust. Flame* 160(11):2476–89
- Xia Y. 2019. *Prediction of thermoacoustic instability in gas turbine combustors*. PhD Thesis, Imperial Coll. London, London
- Xia Y, Duran I, Morgans AS, Han X. 2018. Dispersion of entropy perturbations transporting through an industrial gas turbine combustor. *Flow Turbul. Combust.* 100:481–502
- Xia Y, Laera D, Jones WP, Morgans AS. 2019. Numerical prediction of the flame describing function and thermoacoustic limit cycle for a pressurised gas turbine combustor. *Combust. Sci. Technol.* 191(5–6):979–1002
- Xiong Y, Droujko J, Schulz O, Noiray N. 2021. Investigation of thermoacoustic instability in sequential combustor during first stage lean blow-off. *Proc. Combust. Inst.* 38(4):6165–72
- Yang D, Guzmán-Iñigo J, Morgans AS. 2020. Sound generation by entropy perturbations passing through a sudden flow expansion. *J. Fluid Mech.* 905:R2
- Yang D, Guzmán-Iñigo J, Morgans AS. 2022. Sound generated by axisymmetric non-plane entropy waves passing through flow contractions. *Int. J. Aeroacoust.* 21(5–7):521–36
- Yang D, Laera D, Morgans AS. 2019a. A systematic study of nonlinear coupling of thermoacoustic modes in annular combustors. *J. Sound Vib.* 456:137–61

- Yang D, Morgans AS. 2016. A semi-analytical model for the acoustic impedance of finite length circular holes with mean flow. *J. Sound Vib.* 384:294–311
- Yang D, Morgans AS. 2017a. Acoustic models for cooled Helmholtz resonators. *ALAA J.* 55(9):3120–27
- Yang D, Morgans AS. 2017b. The acoustics of short circular holes opening to confined and unconfined spaces. *J. Sound Vib.* 393:41–61
- Yang D, Sogaro FM, Morgans AS, Schmid PJ. 2019b. Optimising the acoustic damping of multiple Helmholtz resonators attached to a thin annular duct. *J. Sound Vib.* 444:69–84
- Yeddula SR, Guzmán-Iñigo J, Morgans AS. 2022. A solution for the quasi-one-dimensional linearised Euler equations with heat transfer. *J. Fluid Mech.* 936:R3
- Yeddula SR, Morgans AS. 2021. A semi-analytical solution for acoustic wave propagation in varying area ducts with mean flow. *J. Sound Vib.* 492:115770
- Zahn M, Betz M, Schulze M, Hirsch C, Sattelmayer T. 2017. Predicting the influence of damping devices on the stability margin of an annular combustor. In *Proceedings of the ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition*, Vol. 4A: *Combustion, Fuels and Emissions*, V04AT04A081. New York: Am. Soc. Mech. Eng.
- Zhang G, Wang X, Li L, Sun X. 2020. Effects of perforated liners on controlling combustion instabilities in annular combustors. *ALAA J.* 58(7):3100–14
- Zhao D, Li X. 2015. A review of acoustic dampers applied to combustion chambers in aerospace industry. *Prog. Aerosp. Sci.* 74:114–30