Combustion and Flame 169 (2016) 209–215

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

# Flame dominated thermoacoustic instabilities in a system with high acoustic losses

Maarten Hoeijmakers[a,*], Viktor Kornilov[a], Ines Lopez Arteaga[a,b], Philip de Goey[a], Henk Nijmeijer[a]

[a] Department of Mechanical Engineering, Eindhoven University of Technology, The Netherlands
[b] KTH Royal Institute of Technology, Department of Aeronautical and Vehicle Engineering, Marcus Wallenberg Laboratory, Sweden

ARTICLE INFO

*Article history:*
Received 18 September 2014
Revised 6 March 2016
Accepted 10 March 2016
Available online 16 May 2016

*Keywords:*
Intrinsic instability
Thermoacoustics
Combustion instabilities
Acoustic losses

ABSTRACT

The thermoacoustic stability behaviour of a flame is experimentally investigated in the presence of large acoustic losses. Recently it has become clear that under such conditions an instability can occur due to an intrinsic local feedbackloop at the heat source. The experimental results confirm that despite significant acoustic losses, thermoacoustic instabilities can still be present. These findings imply that the effectiveness of passive thermoacoustic damping devices is limited by the intrinsic stability properties of the flame.

## 1. Introduction

The performance of combustion devices is often limited by the occurrence of thermoacoustic instabilities. Such instabilities are induced by a strong coupling between the acoustic field and the flames in a combustor, and may generate unacceptable noise levels or even lead to structural damage [1].

It is generally accepted that thermoacoustic instabilities occur due to the coupling between heat release fluctuations and the acoustic response of the combustion chamber. When the heat release and pressure fluctuations are in phase [2], the flame acts as an amplifier of acoustic waves, which are mostly reflected back towards the flame at the boundaries of the system. Therefore, an unstable feedbackloop can appear where the frequency of the oscillation is typically determined by one of the acoustic modes of the overall system.

Based on the foregoing interpretation, it should always be possible to prevent the unstable interaction by introducing anechoic, i.e. non-reflecive, boundary conditions. In this case, from an energy viewpoint, the flame cannot overcome the damping induced by the acoustic losses.

In contrast, it was recently shown theoretically that the flame may still be unstable even under anechoic conditions [3,4]. The cause for this is that the flame can possess 'intrinsic' thermoacoustic modes. Within this theoretical framework, the flame element contains its own localized feedbackloop, which dominates the flame behaviour under anechoic boundary conditions. It was also shown [3], that for particular systems with only one sided anechoic conditions an unstable system mode can directly arise from such an intrinsic unstable mode of the flame. Therefore, the study of systems with low, but not zero, acoustic reflections allows to reveal the presence of the intrinsic flame instability.

Here, it should be stressed that the found intrinsic instability is of a completely different nature than the extensively studied hydrodynamic and diffusive-thermal instabilities reported in for example [5].

Recently, the intrinsic thermoacoustic instability has also been shown in the setting of direct numerical simulations of a laminar premixed flame [6,7]. On the other hand, in case the flame is intrinsically stable, it is possible to guarantee general thermoacoustic stability when a minimium level of acoustic losses can be achieved [8]. Nevertheless, there have only been few reported experiments of thermoacoustic behaviour under fully or partially anechoic conditions. In some studies using unconfined flames, i.e. flames freely radiating to the environment, the downstream conditions can be considered as anechoic [9–11]. Another notable exception is the studies reported in [12] where the reflection coefficient was actively controlled by means of an active control loop. However, in these studies the experimentally measured instabilities could be explained in the classic sense; the positive feedback of the flame causes destabilization of the acoustic mode. For example, the instability frequencies reported in [9] match the theoretical first, second

---

* Corresponding author.
*E-mail address:* p.g.m.hoeijmakers@gmail.com (M. Hoeijmakers).

http://dx.doi.org/10.1016/j.combustflame.2016.03.009
0010-2180/

and third, quarter wave modes of the closed-open ended duct configuration.

The goal of this work is to experimentally evaluate the thermoacoustic stability of a flame under partially anechoic conditions, and highlight the link to the intrinsic flame modes. To this end, a dedicated experiment is designed and conducted, where the flame/burner is embedded in an configuration with upstream anechoic conditions. Because the downstream boundary conditions are not anechoic, the experimental results alone are not sufficient to unequivocally prove the presence of the flame mode from the experiment alone. Nevertheless, careful consideration of both the theoretical predictions as well as the theoretical findings provides convincing clues that the experimental instabilities are indeed caused by the presence of the intrinsic flame mode.

## 2. Theoretical background

In the one-dimensional modelling of thermoacoustic instabilities, a velocity sensitive flame is usually modelled by a two-step approach. First, the thermal response of the flame is characterized by a flame transfer function, relating the heat release rate $Q$ [W] to acoustic velocity excitation $u$ [m/s],

$$\mathcal{F}(\omega) = \frac{Q'/\overline{Q}}{u'/\overline{u}}, \tag{1}$$

where $'$ and $\bar{x}$ denote the fluctuating and mean parts respectively and $\omega = \omega_\mathrm{r} + i\omega_i$ the complex frequency variable. In the second step, the coupling between heat release and acoustic variables is modelled by the Rankine–Hugionot jump conditions [13,14]. Overall, this leads to the definition of a flame scattering matrix, modelling the acoustic response of the flame. It was recently revealed that under certain conditions on the flame transfer function the flame scattering matrix may be intrinsically unstable due to the local feedback between acoustic velocity and heat release. In particular, the intrinsic poles are given by the solution of,

$$\mathcal{F}(\omega) = -\frac{\epsilon + 1}{\theta}, \tag{2}$$

where $\epsilon = \frac{\rho_c c_c}{\rho_h c_h}$ is the ratio of specific acoustic impedances, and $\theta = \frac{T_h}{T_c} - 1$ is proportional to the temperature ratio. Here, the term 'poles' refers to the (complex) frequency values at which the response of the scattering matrix elements tend to infinity, as is often encountered in control and system theory, see for example [15]. If any of the solutions, the intrinsic poles, of Eq. (2) have an imaginary part $\omega_i < 0$ the flame is intrinsically unstable. And, as a consequence, thermoacoustic instabilities may still occur even in anechoic conditions [3,4].

Thus, in case of an experiment in (nearly) anechoic conditions, one should examine Eq. (2) for clues about the expected behaviour. Since the right hand side is for a fixed temperature ratio merely a constant, a variation in frequency and stability of the poles will typically be caused by variations in the flame transfer function. Figure 1 depicts the general relation between intrinsic mode frequency, stability and the flame frequency response $\mathcal{F}(\omega_r)$. Because any solution will have to satisfy $\angle\mathcal{F}(\omega) = -\pi$, the real part of the pole is, in approximation, determined by the $-\pi$ crossing of the phase of the flame frequency response $\mathcal{F}(\omega_r)$. The stability on the other hand, is determined by the gain at the frequency of the crossing. In general, the pole will be unstable in case the gain is larger than $\frac{\epsilon+1}{\theta}$.

Therefore, given a sufficiently high gain, a variation in the phase characteristic of the flame transfer function will lead to a variation of the frequency of the expected intrinsic poles, and by extension the frequency of thermoacoustic oscillations in anechoic conditions. This expectation forms the target of our experiments. It is well known that for many flames the phase decays linearly due to the time delay nature of the response. As a consequence, any parameter which affects the time delay can be considered an effective method to vary the flame intrinsic poles.

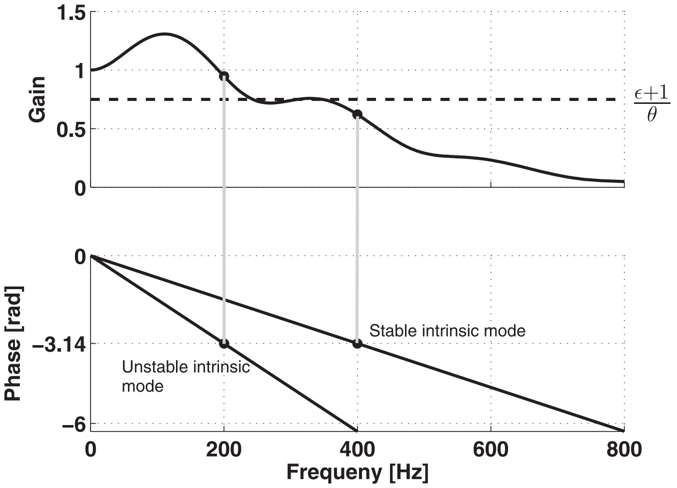

**Fig. 1.** Schematic of the 'rule of thumb' regarding intrinsic mode frequency and stability.

### 2.1. Partly anechoic conditions

In the current case of a partial anechoic setup, any unstable mode is invariably a result of the complete system, i.e. the coupling between acoustics and the flame, and not only of the flame. In essence, adding acoustic reflection, either up- or downstream, will start to move the system poles from the flame-intrinsic modes (open-loop poles) towards a new location [3,16]. As such, both the reflection coefficient and the duct length on the non-anechoic side of the flame become relevant parameters. The extend of the perturbation then depends on the exact choice of length of the duct and reflection coefficient. As such, some downstream lengths are better suited to closely match the behaviour of the intrinsic flame modes than others. An optimal duct-length will hardly shift the stability and frequency of the intrinsic mode, and cause the system mode to be very closely matched to the intrinsic mode. It is important to realize however, that in the absence of an (unstable) flame-intrinsic mode around this frequency, there would be no instability observed at that particular parameter combination.

## 3. Experiment design

In a practical setting it is clear that completely anechoic conditions are extremely difficult, if not impossible, to realize. On the downstream side of the flame for example, the hot combustion gases introduce temperature gradients, which can lead to additional acoustic reflection. In the current contribution we therefore focus on a configuration where only the upstream reflection coefficient is minimized by adding an acoustic horn, see Fig. 2. In the following, it is shown that even under such partly anechoic conditions, Eq. (2) still captures the most important trends.

The overall geometry then is made out of the upstream horn, an inlet for methane, a fan, the burner, and a downstream quartz tube.

In general, one can then recognize three important considerations for the current experimental setup (i) choice of the downstream length, (ii) the horn design, (iii) the choice of the flame and burner