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Thermoacoustic limit cycles in a premixed laboratory combustor with open and choked exits

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ABSTRACT

This paper presents an experimental and theoretical investigation of the response of a turbulent premixed flame during thermoacoustic limit cycle in a simple, laboratory combustor. The flame dynamics are examined using high-speed pressure transducers and CH^* chemiluminescence. The so-called 'interaction index' and time delay between the acoustic velocity fluctuations at the flame holder and the flame's overall heat release fluctuations are then determined. A wide range of operating conditions, traversing the combustor's flammability limits in Mach number and equivalence ratio, are studied for four different combustor exits, including one where the exit is choked. In all cases the time delay correlates very well with the amplitude of the velocity fluctuations. There is also some correlation between the interaction index and these velocity fluctuations, but this is less clear. These results suggest a novel, nonlinear flame model, derived entirely empirically. An existing low-order thermoacoustic model is then extended to include convection and dispersion of entropy fluctuations downstream of the flame, enabling the effect of the choked nozzle to be examined. The novel nonlinear flame model is integrated into the low-order thermoacoustic model, and used to investigate the experimentally observed thermoacoustic limit cycles. The model correctly simulates the observed switch to a low-frequency, entropically driven instability observed when the combustor exit is choked.

1. Introduction

Thermoacoustic instability can arise from a coupling between the acoustic field inside a combustion chamber and the flame's heat release. It is a problem in modern industrial gas turbine design, where the continuing drive for lower NO_x emissions has led to the use of lean premixed combustors which are more susceptible to this instability [1]. In some cases, the amplitude of the pressure fluctuations inside the combustion chamber can become large enough to cause structural damage.

Several low-order thermoacoustic models have been developed for the study of linear and nonlinear dynamics (e.g. [2–10] and review papers [11,12]). An essential part of any thermoacoustic model is the flame model, which relates the heat release of the flame to the acoustic excitation. Many flame models have been proposed, including kinematic models (e.g. [13–16]), other low-order models (e.g. [2,4–7,9,10,17–19]) and the use of computational fluid dynamics (CFD) (e.g. [20–26]).

For example, Dowling [2] proposed the inclusion of a nonlinear saturation on a low-order flame model, later also used by [10,27], limiting the amplitude of the fluctuations and allowing the simulation of limit cycles. The lower limit of the saturation was set at zero, justified by the physical argument that the heat release cannot be negative, and the upper limit was then set at twice the mean heat release to preserve the value of the mean.

There has also been some experimental investigation of the response of laminar and turbulent premixed flames to imposed velocity fluctuations [28–32]. Bellows et al. [28] found that their turbulent flame response saturates at large forcing amplitudes, but the non-dimensional heat release fluctuation amplitude at which the nonlinearity becomes evident depends strongly on the Reynolds number, the equivalence ratio and the forcing frequency. The phase of the flame response is similarly complex. Refs. [29,30,32] identify the shedding of vortices from the flameholder as having a major effect on the observed flame response.

Computational fluid dynamics modelling of the flame coupled with low-order modelling of the acoustics may model flame nonlinearity, but are significantly more expensive computationally [26,33–36]. Thus, experimentally derived low-order models of flame nonlinearity continue to be useful in understanding the thermoacoustic problem. Use of a flame model relating the heat release fluctuations to the acoustic fluctuations through an 'interaction index' n and a time delay τ (see Section 3.3) were well illustrated by Crocco and Cheng [17]. Dowling [2] shows that for linear acoustics in homogeneous flow,

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Nomenclature

A	area
AR	downstream nozzle area ratio
$\mathbf{B}$	boundary condition matrix
b	location of heat input plane
c	speed of sound
c_p	specific heat at constant pressure
$F(g)$	fourier transform of quantity g
f	acoustic wave characteristic
g	acoustic wave characteristic
h	acoustic wave characteristic
j	acoustic wave characteristic
I	emission intensity
l	index
L	location of downstream end of combustor
$\dot{m}$	mass flow rate
M	mach number
n	interaction index, mode number, counter
p	pressure
q	heat release rate
r_{xy}	cross-correlation between quantities x and y
s	entropic wave characteristic
T	temperature
t	time
u	velocity
x	spatial coordinate
$\mathbf{X}$	model coefficients matrix
$\mathbf{Y}$	model coefficients matrix
γ	ratio of specific heats
ϕ	equivalence ratio
ρ	density
ρ_{xy}	correlation coefficient between quantities x and y
τ	time delay
ω	angular frequency

Subscripts and modifiers

g'	fluctuating part of quantity g
$\bar{g}$	mean part of quantity g
1,2	station
d	downstream of the flame
g	at the flameholder
rms	root mean square
s	entropic
t	stagnation
u	upstream of the flame

$$\frac{p'}{\bar{p}} \sim O(\gamma\overline{M})\frac{u'}{\bar{u}}, \tag{1}$$

so that in a low Mach number flow the fractional pressure fluctuation remains small even when $u'/\bar{u} \sim O(1)$. A similar analysis shows that the fractional density and temperature fluctuations are also small in comparison to the fractional velocity fluctuations. Thus, as is commonly done in studies of premixed combustion, it is reasonable to assume that the acoustic velocity fluctuations are the main excitation of the heat release fluctuations in the flame, and to neglect the effect of the fluctuations in other quantities [2,4,13,14,31,37–39].

The boundary conditions must also be considered. Whilst thermoacoustic instability has been studied extensively in premixed combustors over the last few decades, most studies have concentrated on combustors with acoustically open exits. The effect of a choked exit nozzle has received less attention [40–42]. This is an important omission, given that some of those studies that have been carried out suggest that a choked exit nozzle can have a strong effect on the system stability [3,40,42,43], and that most in service combustors feature a choked, or nearly choked, nozzle downstream of the combustion chamber.

Such behaviour with a choked exit can perhaps be explained by Marble and Candel's [44] theoretical work, which showed that a choked nozzle produces upstream travelling pressure fluctuations in response to incident acoustic pressure and convected entropy fluctuations. MacQuisten and Dowling [40] reported a strong low-frequency instability in their combustor when the exit was choked, and speculated that this was the cause. Hield and Brear [42] also observed a similar low-frequency instability, and showed experimentally that the conversion of incident entropy disturbances to upstream travelling sound can be significant.

Taking these incident entropy fluctuations into account, Keller [1] developed a simple model for the frequency of entropically driven instabilities in a combustion chamber with a choked downstream boundary condition, in which the main driver of the instability is the upstream travelling acoustic wave generated as the entropy fluctuation from the flame convects through the downstream nozzle. The dominant (i.e. slowest) timescale in this mechanism is the convection time of the entropy perturbation, which leads to oscillations at frequencies lower than those typical for acoustically driven instability,

$$f_n = (2n-1)\frac{\bar{u}_2}{2(L-b)} + O\big(\overline{M}_2\bar{u}_2/(L-b)\big). \tag{2}$$

Similarly, Zhu et al. [26] performed numerical simulations of a combustion chamber with a spray atomiser, and compared open and choked downstream boundary conditions. They showed that a choked nozzle downstream of the combustor leads to limit cycles that are not present with the open exit, and demonstrated the link between the convection of the entropy fluctuations generated by the flame and the cycle frequency. Although they did not give an explicit formula for the frequency, they stated that: "the period of oscillation is approximately twice the convection time through the combustor", which is equivalent to the formula from Keller [1]. Finally, Dowling and Stow [45] reviewed the methods of modelling thermoacoustic instability and showed the importance of including the entropy waves and their dispersion downstream of the flame when modelling systems with choked exits, in order to correctly model the low-frequency convection modes.

However, it is noted that not all authors agree that a choked combustor exit is the cause of low-frequency limit cycle behaviour. Eckstein et al. [41] found no difference between the behaviour of their combustor with open and choked exits, and concluded that the limit cycle was due to the convection timescale of the fuel from the injector to the flame.

At first sight these results appear contradictory, but there are differences in the combustor designs. In those combustors where the instability was due to the choked exit [40,42,43], the flame is relatively long and burning occurs almost up to the combustor exit. In contrast, the flame of Eckstein et al. [41] is shorter, with a long convection time before the exit nozzle. This may allow the entropy fluctuations generated by the flame to dissipate before reaching the nozzle. Polifke et al. [46] showed that the amplitude of the reflected pressure wave (and therefore the limit cycle formed) was dependent on the amplitudes and relative phase of the incident waves, as the upstream travelling pressure fluctuations due to the incident entropy and pressure fluctuations may interact either constructively or destructively. Thus, the amount of dissipation of