Combustion and Flame 172 (2016) 309–325

Contents lists available at ScienceDirect

Combustion and Flame

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

Investigation of intermittent oscillations in a premixed dump combustor using time-resolved particle image velocimetry

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ARTICLE INFO

Article history:
Received 26 November 2015
Revised 19 December 2015
Accepted 14 June 2016
Available online 6 August 2016

Keywords:
Combustion instability
Dump combustor
Intermittent bursts
Time-resolved particle image velocimetry
Dynamic mode decomposition
Wavelet transform

ABSTRACT

The present work deals with time-resolved investigation of the flow field during acoustic self-excitation by a lean premixed flame in a dump combustor. Simultaneous measurements of unsteady pressure, velocity fields using time-resolved particle image velocimetry (TR-PIV) and CH^* chemiluminescence are performed. As the equivalence ratio is varied, conditions of maximum pressure amplitude correspond to the prevalence of intermittent bursts in all the measured quantities. The intermittency is quantified by means of the permutation entropy of the pressure signals. The most significant frequencies are identified with the fundamental natural duct acoustic mode and the large-scale vortex roll-up ("wake mode") frequency. The simultaneous occurrence of these multiple frequencies and shifts in their relative dominance of frequencies over time, shown by wavelet transform, result in the observed intermittent burst oscillations. Regimes of these ordered oscillations alternate with those of relative silence as well. The dynamic mode decomposition (DMD) of the TR-PIV data during windows of decay and growth of intermittent oscillations in the pressure signal quantifies the contribution of the above dominant modes in terms of their temporal growth rates. Besides the above two modes, the flapping mode and the shear layer mode of the flow field are also indicated. Consecutive PIV realisations and chemiluminescence images in a time-resolved sequence during excitation of high pressure amplitude show the large-scale vortex roll-up to substantially convolute the flame, leading to high heat release fluctuations. A further sequence of consecutive flow/flame fields is also examined as to how oscillations emerge out of a relatively silent time interval. The Kelvin–Helmholtz structures of the shear layer mode prevalent during the silent regime are seen to undergo a collective interaction to form a large-scale structure that excites the vortex and acoustic modes in turn.

1. Introduction

Combustors are generally designed to have physical constructs that enable recirculation of fluid flow for flame-holding. The hydrodynamics of the recirculation zone involves fluid dynamic instabilities that couple with acoustic oscillations in the duct excited by an oscillatory flame anchored there, leading to combustion instability. Understanding these mechanisms are vital in developing reduced order models and control strategies to mitigate the instabilities.

As the operating conditions of a combustor are varied, it tends to switch from low pressure-amplitude broadband oscillations that are considered to be stable, to high amplitude discrete tones that are deemed unstable. Early studies [1–3] delineate the comparison of these two states of operation and/or focus mainly on characterising the unstable state. However, in recent times, there is growing interest in reporting or exploring the transition behaviour of the oscillations from the stable to the unstable states [4–10].

Let us first look at the observations reported in these investigations on the above transition behaviour. Lieuwen [4] has examined the bifurcation in the combustor behaviour, and found it to exhibit supercritical and subcritical bifurcations at different conditions, each at a constant frequency. Altay et al. [5] have considered a premixed dump combustor with varying equivalence ratio at a constant inlet Reynolds number, where they observe sharp rise in amplitudes at high equivalence ratios. The instability is at the dominant acoustic modes, one of which is at a high frequency (5/4th wave mode), and two of them at the fundamental natural frequency (1/4th wave mode). Among the latter two, one is identified as quasi-stable, based on an intermediate level of amplitude excited, whereas the other is designated unstable, being at quite high amplitudes.

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http://dx.doi.org/10.1016/j.combustflame.2016.06.018

Earlier, Yu et al. [6] have reported abrupt shifts in the frequencies with increase in the inlet velocity, which has been systematically varied at constant equivalence ratio in a dump combustor with an exit nozzle configuration. Similar abrupt shifts in frequencies were identified at the onset of instability in a dump combustor with non-premixed [7] and partially premixed [8] fuel injection, as well as in a V-gutter stabilised flames [9], when the inlet velocity was systematically varied, maintaining a constant fuel flow rate. The shift in the dominant frequency accompanied by the growth in amplitudes is understood as the bifurcation of the combustor behaviour.

In his bifurcation study, Lieuwen [4] has highlighted the stochastic triggering of the combustor, exhibited by the burst phenomenon before reaching a limit cycle. Such intermittency is recently described within a nonlinear dynamical systems framework as an essential feature en route to limit cycle oscillations for a bluff-body stabilised combustor [10]. Gotoda et al. [11] have adopted a similar approach, and characterised the transition from chaotic to ordered oscillations in terms of the permutation entropy (PE or "petropy"). A non-physical data driven approach to amplitude variations is also recently reported to distinguish the onset of high-amplitude oscillations in a swirl combustor [12]. However, these descriptions do not explain the exact nature of the physical processes and their interaction that cause the above intermittent behaviour.

In the present paper, we focus on the physical mechanism of intermittent oscillations of sufficiently high amplitudes that could eventually lead to limit cycle. Studying the physics in detail requires restricting the attention to a particular geometry of the flow recirculation zone and its hydrodynamics. However, the outcome of the investigation would be illustrative of how to understand the intermittency in other similar geometries. In the present work, we adopt the dump combustor geometry containing a backward-facing step.

Turning to the physical mechanism involved as reported in the past works, most of the above investigations [1,2,5–8] are found to highlight the prevalence of large-scale vortical structures under unstable conditions in a dump combustor. Early on [1,2], the heat release rate fluctuations could directly be related to the vortex dynamics in the flow field. Schadow and Gutmark [13] describe the mechanism of "vortex combustion", i.e., combustion in the large-scale coherent vortical flow structures in a dump combustor. They have elucidated that premixed combustion commences at the interface of entrained fresh reactants and combustion products. Ghoniem et al. [14] showed earlier that the unstable mode reported by Altay et al. [5] formed a Strouhal number $St = 0.14$ based on the observed dominant frequency, the step height at the dump plane, and the inlet bulk velocity, which we shall identify as the 'vortex mode' in the present paper. Yu et al. [6] have reported the presence of large-scale vortices in the combustor to accompany the abrupt shift in frequencies. The simultaneous presence of dominant acoustic and vortex time scales is shown to be prevalent during the instability. Similarly, the bifurcations reported in [7,8] involve shifts between the acoustic and vortex modes that follow constant Helmholtz and Strouhal number trends with Reynolds number in their respective regimes of dominance.

It is evident from the above works that the interaction of the acoustic and vortex modes is involved in the transition from stable, noise conditions to unstable, limit cycle conditions. Naturally, the intermittency that marks such transition may be expected to involve processes with multiple characteristic time scales. While the vortex mode in the dump combustor geometry may be predominant in interacting with the acoustics of the duct under unstable conditions as seen in most of the above cases, there are other hydrodynamic modes prevalent in the associated flow field that could play a role in causing intermittency during the transition. This forms the basis of the present work.

The dump combustor geometry is widely studied in the non-reacting fluid dynamics literature as flow past a backward-facing step [15–17]. This literature has identified multiple hydrodynamic modes to co-exist in this seemingly simple flow geometry, which causes intermittency even under non-reacting flow conditions without acoustic feedback [18]. The frequencies of the hydrodynamic modes can be non-dimensionalised to form Strouhal numbers based on the inlet velocity U, and the step height h or the momentum thickness $\theta$of the flow approaching the step. For non-reacting flows, the characteristic Strouhal number range based on θ is $St_\theta \sim$ 0.007–0.017 for the 'shear layer mode', which is based on the Kelvin–Helmholtz (K–H) instability [19], the Strouhal number based on h is St_h ~0.14–0.27 for the 'wake/step mode' [14,20] (referred to as the vortex mode [6–9]), and $St_h \sim 0.05$ for the 'flapping mode' [15].

Under combustion conditions and with acoustic feedback, additional interactions occur between these hydrodynamic modes and the acoustic mode of the duct. In fact, under conditions of high-amplitude excitation in a swirl combustor, a nonlinear interaction of one of the dominant hydrodynamic modes, namely, the processing vortex core (PVC), with the acoustic mode is observed by way of an additional frequency of oscillations that is a combination of the frequencies of these two modes [21,22]. However, such interaction of hydrodynamic and acoustic modes could also cause intermittent pressure oscillations that eventually lead to fully excited combustion instability. It is observed in the present work that the dominant mode of oscillations switches from time to time between acoustic and hydrodynamic modes, interspersed with the prevalence of regimes of relative silence in between, marking such intermittency.

Investigation of such intermittent oscillations, the related mode switches, and their physical mechanism is possible mainly by means of time-resolved diagnostics. Intermittency is investigated even under cold flow conditions by means of time-resolved particle image velocimetry (TR-PIV) of the backward-facing step flow and application of dynamic mode decomposition (DMD) to such flow fields [18]. TR-PIV has been extensively used to study acoustic instabilities in a swirl combustor [21,23]. To illustrate how the flow and acoustic fields are correlated, for instance, the precessing vortex core (PVC) is shown to be affected by the longitudinal acoustic mode through its stretching and contraction [21]. Large scale changes in the heat release were also found to be caused by the radial flow in the PVC. The flow features between the "noisy" (actually, unstable) and the "quiet" (stable) operation of the combustor have been compared, wherein the PVC was found to be absent in the latter case [23].

In the context of the dump combustor, TR-PIV is reported by Hong et al. [24], who show the phase averaged velocity fields during the limit cycle oscillations. The velocity fields clearly show changes in the recirculation bubble across the various phases of the acoustic cycle, and corresponding curving of the flame brush to align with the flow changes. In the above work, the flame front is depicted to be attached to the step corner at all times, as it was deduced based on the jump in the density of seeding particles in the raw PIV images. However, in the preceding work by the same research group [5], time-resolved sequences of flame images are shown at different conditions corresponding to the high-frequency unstable, fundamental mode unstable and quasi-stable conditions, contrasted against the sequence of flame images under stable conditions. These sequences show marked changes in flame standoff distance from the step corner for the different modes, and significant standoff fluctuations within each sequence.