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Flame dynamics during intermittency in a turbulent combustor

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Abstract

On the reduction of equivalence ratio from stoichiometry to lean conditions, turbulent combustors exhibit intermittency before and after the occurrence of thermoacoustic instability. In this paper, we compare the dynamic characteristics of this intermittency prior to and post thermoacoustic instability. The analysis of the unsteady pressure fluctuations within the combustor suggests that the intermittency prior to and post thermoacoustic instability are of type II. We also compare the flame dynamics during either state using high speed Mie scattering images acquired simultaneously with unsteady pressure. We observe that during both regimes of intermittency, the flame switches between two distinct patterns of oscillations; one where the flame oscillates in an aperiodic manner due to the inherent turbulent fluctuations, and another where the flame exhibits periodic roll-up as a consequence of the periodic vortex shedding at the dump plane. Nevertheless, it is observed that the flame dynamics during intermittency prior to and post the occurrence of thermoacoustic instability are different. During intermittency before the occurrence of thermoacoustic instability, the flame along the inner shear layer is stabilized by the stagnation point flow behind the bluff body. In contrast, during intermittency after the occurrence of thermoacoustic instability, the flame along the inner shear layer is stabilized by the recirculation zone created by the bluff body.

Keywords: Intermittency; Turbulent combustion; Flame dynamics; Reactive; Flow dynamics

1. Introduction

Recent studies on combustors with turbulent reactive flow and flame stabilization using swirl [1] or bluff body [2] show that on approaching lean equivalence ratios, the reactive flow system exhibits intermittency presaging the onset of thermoacoustic instability. It was also seen that as the equivalence ratio was further reduced, the system undergoes another bifurcation and exhibits intermittency post the occurrence of thermoacoustic instability [3, 4]. On further reduction in equivalence ratio, the flame blows out. Further, statistical measures that quantify intermittency were proposed as precursors to impending thermoacoustic instability [5]. Nevertheless, till date, the similarities and differences between these intermittent states prior to and post thermoacoustic instability have not been systematically investigated. The primary goal of this paper is

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to compare and contrast either state both from the perspective of dynamical systems theory and from the point of view of flame dynamics.

In the context of turbulent flows, intermittency is a well-studied phenomenon that was observed from the early research of Batchelor and Townsend [6]. However, different types of intermittent behaviors are observed in turbulent flows. The interface between the turbulent fluid inside the boundary layer and the irrotational flow outside the boundary layer is found to be intermittent. Further, it is known that the dissipative range of turbulent cascade exhibits intermittency [7]. Additionally, the wall boundary layer exhibits intermittency caused by the formation of coherent structures that breaks down intermittently, producing bursts of small-scale turbulence [8].

In contrast, the intermittency that we focus on in this paper is the dynamic state of a system with confined turbulent reactive flow that is characterized by bursts of periodic pressure oscillations appearing amidst aperiodic pressure fluctuations in an apparently random manner [2, 9]. In the context of the onset of thermoacoustic instability, Nair and Sujith [9] showed that the intermittent dynamics prior to thermoacoustic instability corresponds to dynamics in a homoclinic orbit in the phase space. Further, Nair and Sujith [4] attributed aperiodic flame extinction and re-ignition events as the cause for the presence of the bifurcation that leads to the occurrence of intermittency after the occurrence of thermoacoustic instability, before eventually reaching blowout. The multifractal characteristics of these oscillations, prior to and post thermoacoustic instability, was recently studied by Unni and Sujith [3]. They observed that combustion noise (pressure oscillations during near stoichiometric combustion) and pressure oscillations prior to lean blowout have similar multifractal characteristics. Nevertheless, they did not discuss the characteristics of intermittency before and after the occurrence of thermoacoustic instability. In this paper, we provide a detailed comparative analysis of intermittency prior to and post thermoacoustic instability.

The presence of intermittency helps us forewarn about the dynamic transitions in a turbulent combustor. Hence, understanding the characteristics of intermittency is important to improve the forewarning capabilities. Through a comparative analysis of the intermittency occurring prior to and post thermoacoustic instability, we wish to improve our understanding of the physics of intermittency. There are two specific objectives for this study. (1) Compare and contrast the intermittency occurring prior to and post thermoacoustic instability using unsteady pressure time series measurements. (2) Study the flame front dynamics during either state using high speed Mie scattering images, acquired simultaneously with unsteady pressure.

The rest of the paper is laid out as follows. Section 2 describes the experimental setup. Section 3 talks about the results and discussions. Major conclusions are detailed in Section 4.

2. Experimental setup

The combustor used for the present work is the test rig that was used by Nair et al. [2]. It is a backward facing step combustor with a provision to use a bluff body as the flame stabilizing device (Fig. 1). The combustion chamber has a cross-section of $90 \times 90\ mm^2$. The length of the combustion chamber for the current experiments is fixed at 800 mm. The fuel used here is LPG (60% Butane and 40% Propane). The fuel is injected 120 mm upstream of

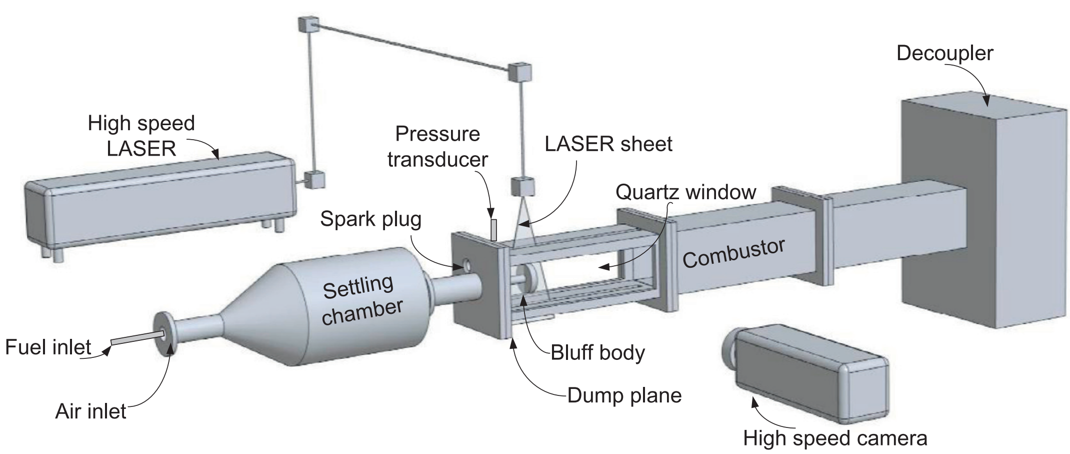

Fig. 1. Experimental setup used for the present study. The design of the combustor is adapted from Komarek and Polifke [10].