Investigation of Lifted Flame Propagation Under Pulsing Conditions Using High-Speed OH-LIF and LES

V. N. Prasad · M. Juddoo · A. Kourmatzis · A. R. Masri

Received: 9 February 2014 / Accepted: 1 July 2014 / Published online: 24 July 2014
© Springer Science+Business Media Dordrecht 2014

Abstract Flame propagation in a lifted flame subjected to a transient velocity pulse is investigated using high-speed OH-LIF and Large Eddy Simulation (LES). The design of the burner, taking the requirements of the simulations into consideration, comprises an attached and lifted CNG jet flame in a mild air co-flow, forced to transition by a controlled mass flow pulse of fuel. The high-speed images taken at 5 kHz show a rapid lifting of the flames upon pulsation before the flame base propagates back towards the nozzle. The resulting steady state position differed from the initial lift-off position, consistent with the previously observed hysteresis concept. Calculations using LES along with detailed chemistry are shown to capture the basic features observed in the experiment.

Keywords Lifted flames · Transient flame · Large eddy simulation · High speed OH-PLIF

1 Introduction

Transient processes such as flame extinction or velocity pulsations due to pressure drops are often encountered in practical combustion devices such as in aero-engines. These processes can have a negative impact on efficiency and stability and can lead to the extinction or blow-off of the flame which is generally lifted from the burner’s lip and has extensive inhomogeneities at its base [1–3]. To determine the extent of the impact of these critical events, a comprehensive understanding of fundamental unsteady processes that occur in the stabilization region of lifted flames is necessary. In these regions, complex interactions between turbulence and chemistry occur on a wide range of temporal and spatial scales.

Experimentally, the advent of high-speed laser imaging of selected reactive scalars such as hydroxyl (OH) and formaldehyde (CH₂O) has enabled the investigation of transient
processes and an example of this is the recent imaging of flame holes in highly sheared non-premixed flames [4, 5]. However, analysis is mostly limited to two dimensions unless more sophisticated setups involving multiple lasers and cameras are involved [6, 7]. Furthermore, current repetition rates are commonly 5-10 kHz, which is often not sufficient to resolve transient processes adequately, particularly in high Reynolds number flows. While higher repetition rates of the order 20 kHz can be achieved, this is only at the sacrifice of spatial resolution, which for turbulent flames is desirable in order to resolve a wide range of length-scales. An alternative way of achieving high speed image acquisition involves utilizing pulsed burst technology as demonstrated in [8, 9].

Advances in numerical simulations, particularly in Large Eddy Simulation (LES), can readily provide quantities which are otherwise not currently easily accessible using well established experimental techniques. LES simulations have shown promising potential in describing turbulent combustion in laboratory scale burners [10] as well as in industrial burners [11, 12] and in providing predictions of unsteady processes [13]. Unlike in typical high repetition rate experiments, the time scales limited by the Courant-Friedrichs-Lewy (CFL) criterion are sufficient to describe the motions of all spatially resolved scales. Impeorative to reliable simulations are adequate modelling of the unresolved turbulence chemistry interactions, the employed numerics and the grid resolution. While the latter depends mainly on the available computational resources, the employed models still require validation to achieve sufficient confidence.

Current validation cases for numerical simulations like those developed in the framework of the TNF workshop such as the Sandia flames [14, 15] are mainly limited to measurements of time-averaged and conditional flame statistics and very few experiments provide data of transient processes. As an example of such transient target cases, the spark ignition experiment by Ahmed et al. [16] may be useful, where the flame kernel formation and flame propagation upon ignition was measured with a high-speed system. Wang et al. [17] recently applied a velocity pulse to a turbulent piloted non-premixed flame and recorded the resulting flame extinction and re-ignition. Arndt et al. [18] have used similar pulsing approaches to investigate auto-ignition of methane jets in a hot co-flow.

The objective of this work is to enhance and validate simulation tools like Large Eddy Simulation (LES) in situations where unsteady flame propagation occurs. For this purpose, a lifted flame in an ambient co-flow, steady state cases of which have been widely examined in the literature [19–22], is forced to transition by a controlled velocity pulse. The subsequent movement of the flame base, which provides a quantifiable indicator of the transient process, is recorded with a high-speed laser imaging system. The velocity pulsing arrangement is similar to that employed earlier by Wang et al. [17]. Some desirable criteria facilitating aspects of the simulations such as the required grid resolution or the overall duration of the process are taken into consideration. The paper is structured as follows. First, an overview of the experimental setup is given. Qualitative high-speed images are then presented followed by quantification of the lift-off heights and lift-off velocities. Finally, some of the outcomes of initial LES calculations are discussed.

2 Experimental Setup

A schematic of the experimental setup is presented in Fig. 1 showing the equipment used to generate the pulse, the burner, and co-flowing wind-tunnel. The burner is a simple tube, 7.4 mm in diameter (D) with a wall thickness of 0.25 mm. The fuel used here is compressed natural gas (CNG) which contains 88.8% CH₄, 7.8% C₂H₄, 1.9% CO₂ and 1.2%