Combustion and Flame 191 (2018) 39–52

Contents lists available at ScienceDirect

Combustion and Flame

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

Leading edge dynamics of lean premixed flames stabilized on a bluff body

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ARTICLE INFO

Article history:
Received 22 May 2017
Revised 6 July 2017
Accepted 14 December 2017

Keywords:
Unsteady laminar flame
Flame leading edge
Laminar premixed flame
Bluff body flames

ABSTRACT

This paper examines the dynamics of the flame leading edge in a laminar premixed CH_4/air flame stabilized on a bluff body in a channel. Harmonic fluctuations and step velocity change are used to simulate the flame response to acoustic oscillations, which are of primary importance in the study of thermo-acoustic instabilities. We use a fully resolved unsteady two-dimensional code with detailed chemistry and species transport, with coupled heat transfer to the bluff body. Calculations were conducted with different equivalence ratios, body materials, and steady state inlet velocity with step or harmonic perturbations. Results reveal that the flame leading edge dynamics displays a peak response around St = 0.5 suggesting that the leading edge motion is mainly due to the advection of appropriate ignition conditions as a result of the excitement of the wake recirculating flow. There is considerable augmentation of the flame wrinkles generated by the flame leading edge motion as result of the flow–flame interaction. Additionally, we show that a flame that anchors on average further upstream leads to stronger damping of the shear layer vortices and thus weaker vortex-flame interaction and heat release fluctuations. Hence, we identify two different mechanisms by which the flame leading edge location and oscillation amplitude impact heat release fluctuations. The study suggests a stronger dependence of the overall flame wrinkling and heat release fluctuations on the flame leading edge dynamics than recognized previously and the potential role it plays in combustion dynamics.

1. Introduction

In industrial combustors and propulsion systems the reactants velocity is orders of magnitude higher than the laminar burning velocity, thus a recirculation zone generated at the wake of a bluff body is a common way to provide a low velocity region where the flame can stabilize. Bluff body stabilized flames are susceptible to combustion instabilities due to various coupling processes between combustion, flow structure and acoustic [1]. Such instabilities generate oscillations in pressure, heat release and heat flux to the walls, which can result in structural damage, flashback or blowoff. Combustion instability originating from vortex–flame interactions is frequently observed in premixed combustion systems [2]. The underlying mechanism [3–5] is thought to be the shedding of vortices due to velocity perturbation of the shear layer, and the periodic heat release oscillations associated with the vortex–flame interaction, which couples with the pressure oscillations if they are in phase, according to the Rayleigh criterion.

The relationship between the flame and the acoustic field in this regime can be described by a transfer function between the heat release and velocity (or pressure) fluctuations. A transfer function of a laminar premixed ducted flame was developed by Fleifil et al. [6] and later extended to conical flames by Schuller et al. [7]. The impact of the flame anchoring dynamics on conical flames has drawn significant attention. Schreel et al. [8] measured experimentally the acoustic transfer function of a burner stabilized premixed flat flame. The experiments showed a resonance with a peak gain that depends on the flame holder material, with lower amplification when using a lower thermal conductivity flame holder that resulted in a higher surface temperature. Rook et al. [9,10] developed analytical and numerical models that showed that the resonance response originates from heat transfer coupling between the flame consumption speed and heat loss mechanism. Atlay et al. [11] extended the planar flame models of perforated plate stabilized flames to include flame area oscillations, and demonstrated good agreement with experimental measurements. Kedia et al. [12,13] included the heat transfer in the flame holder in his analytical model and in the fluid–solid coupled numerical simulations,

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https://doi.org/10.1016/j.combustflame.2017.12.020

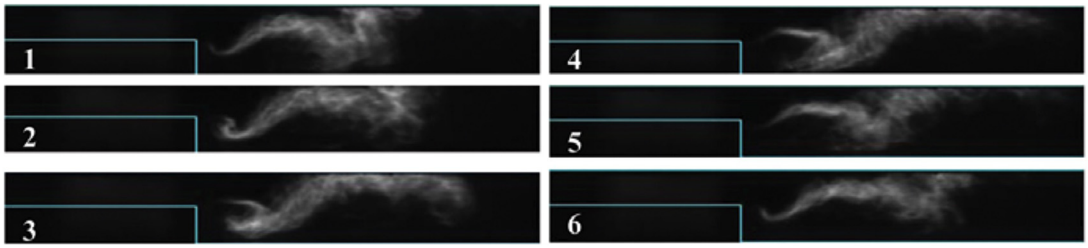

Fig. 1. A sequence of flame chemiluminescence images (Reproduced from Ref. [20]) with interval of 2.5 ms between images, from an acoustically coupled backward facing step combustor at equivalence ratio of 0.85, inlet temperature of 300 K, Reynolds number of 6500 and ceramic step. The images show the periodic motion of the flame base/leading edge and the rollup of the flame surface downstream associated with vortex shedding.

and showed its importance for predicting the surface temperature and flame transfer function.

Cuquel et al. [14] introduced the flame leading edge (or base) dynamics from Rook et al. [10] into a kinematic flame model of a conical flame and validated the model experimentally. Their model demonstrated the important role of the flame leading edge dynamics in determining the non-linear flame response to velocity fluctuations. Experimental investigation in a slot burner by Mejia et al. [15] demonstrated the impact of the flame holder temperature on the flame leading edge motion and the flame transfer function, which lead to transition from unstable to stable operation as the temperature of the flame holder increased. They show that at higher body temperature the flame leading edge motion is smaller, which leads to lower wrinkling of the flame according to kinematic considerations described by Cuquel et al. [14].

Application of a similar kinetic model to bluff body stabilized flames was accomplished by Dowling [16] and Lieuwen [17], assuming that under velocity fluctuations smaller than the mean velocity (no negative inlet velocity) the flame remains attached to the downstream corner of the bluff body. Experimental measurements by Shanbhogue et al. [18] on an acoustically forced bluff body stabilized flame were compared to a kinematic model, concluding that the key processes controlling the flame dynamics include the excitation of the flame front by the vortical structures formed by the oscillating flow, the anchoring of the flame on the body, and kinematic restoration of the flame surface. The first two processes are dominant near the body and the third is observed downstream where the vortices decay. The non-linear response leading to saturation of the response at higher forcing amplitudes was related to flame kinematics that smooth out the flame wrinkles. The assumption of flame attachment provided good correspondence between the model and experiment regarding the flame sheet displacement normal to the undisturbed flame close to the bluff body for forcing amplitudes of 1% of the mean inflow velocity. Preetham et al. [19] extended the kinematic model of laminar premixed flames forced by harmonic velocity perturbations, and included flow disturbances with arbitrary convective velocity. They showed that the flame wrinkles generated by the flame anchoring and velocity non-uniformities can either constructively or destructively superpose, depending on the flame shape mean flow velocity phase speed of the shear layer instability wave and frequency. In this work, we look at bluff body flames and relax the assumption of flame attachment to the bluff body, thus by allowing perturbations that originate from the attachment point to contribute to flame wrinkling. Moreover, we consider the flame and flow interaction though flame stretching, gas expansion, and baroclinic torque. Therefore, we expect to see the result of the superposition of flame surface oscillations originating from the shear layer instability and from the flame anchoring.

The significant periodic displacement of the flame leading edge as result of acoustics is evident in Fig. 1, which is taken from the experimental investigation of Hong et al. [20] on lean premixed flames in a backward facing step combustor. In Fig. 1 we present a sequence of flame images during relatively weak oscillations. The significant impact of vortices on the flame during acoustic oscillations leads to increase in the heat release and sustains combustion dynamics. The measurements showed that a ceramic step broadened the stable operating conditions in comparison to a steel step (shown in Hong et al. [20]).

Kedia and Ghoniem [21] investigated the response to harmonic forcing of laminar premixed flames stabilized on a heat conducting bluff body. They showed difference in the heat release and heat flux to the bluff body for different flame holder materials, but the frequency dependence and associated physical mechanism were not studied in detail because they limited the analysis to a single forcing frequency. A possible mechanism for the impact of flame holder heat transfer properties on the flow structure was revealed in detailed numerical simulations of Michaels and Ghoniem [22] on steady laminar bluff body stabilized flame. It was found that for a flame holder with lower thermal conductivity the flame stabilizes further upstream and closer to the shear layer, resulting in stronger decay of vorticity downstream and thus weaker vortex–flame interaction. Berger et al. [23] analyzed the same configuration but with isothermal boundary conditions at the bluff body surface, and showed that as the flame holder temperature increased the flame moved further upstream and the recirculation zone shortened.

In this work, we look at unsteady bluff body stabilized flames and investigate the impact of the flame leading edge dynamics on heat release oscillations. We examine if the impact of the flame leading edge location is mainly through modification of the flow field, as suggested by Michaels and Ghoniem [22], or there are also significant heat release oscillations due wrinkles produced by the flame leading edge motion, as suggested by Cuquel et al. [14] for conical flames.

In the present paper, we conduct harmonic forcing simulations over a range of forcing frequencies and conditions, and also compute the response to an inlet velocity step in order to investigate: (a) The flame leading edge dynamics and (b) The Impact of the leading edge dynamics on heat release oscillations. We first look at the leading-edge kinematics, which displays a peak response at a certain Strouhal (St) number, defined by the frequency times the bluff body height and divided by the inflow velocity. Next, we analyze the conjugate heat transfer with the bluff body and the flame structure, and elucidate the impact of heat losses and flame stretch on the flame leading edge dynamics. Subsequently, we look at how the leading-edge dynamics influences the flow field. The results suggest two important mechanisms by which the flame leading edge dynamics impact heat release oscillations. The first mechanism is the advection of flame wrinkles generated by the motion of the leading edge, which result in peak response at $St = 0.5$ for the present study. The second mechanism is through the impact of the flame leading edge location on the flow field and strength of the vortices impinging the flame, which has a predominant impact on the magnitude of heat release oscillations. Finally, we provide insight on the role of the leading-edge dynamics on the