Combustion and Flame 162 (2015) 1304–1315

Contents lists available at ScienceDirect

Combustion and Flame

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

The blow-off mechanism of a bluff-body stabilized laminar premixed flame

Kushal S. Kedia, Ahmed F. Ghoniem *

Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA

ARTICLE INFO

Article history:
Received 21 April 2014
Received in revised form 28 October 2014
Accepted 29 October 2014
Available online 20 November 2014

Keywords:
Premixed flame
Blow-off mechanism
Bluff-body
Laminar
Conjugate heat exchange

ABSTRACT

The objective of this work is to investigate the dynamics leading to blow-off of a laminar premixed flame stabilized on a confined bluff-body using high fidelity numerical simulations. We used unsteady, fully resolved, two-dimensional simulations with detailed chemical kinetics and species transport for methane–air combustion. The flame–wall interaction between the hot reactants and the heat conducting bluff-body was accurately captured by incorporating the conjugate heat exchange between them. Simulations showed a shear-layer stabilized flame just downstream of the bluff-body, with a recirculation zone formed by the products of combustion. The flame was negatively stretched along its entire length, primarily dominated by the normal component of the strain. Blow-off was approached by decreasing the mixture equivalence ratio, at a fixed Reynolds number, of the incoming flow. A flame is stable (does not undergo blow-off) when (1) flame displacement speed is equal to the flow speed and (2) the gradient of the flame displacement speed normal to its surface is higher than the gradient of the flow speed along the same direction. As the equivalence ratio is reduced, the difference between the former and the latter shrinks until the dynamic stability condition (2) is violated, leading to blow-off. Blow-off initiates at a location where this is first violated along the flame. Our results showed that this location was far downstream from the flame anchoring zone, near the end of the recirculation zone. Blow-off started by flame pinching separating the flame into an upstream moving (carried within the recirculation zone) and a downstream convecting (detached from the recirculation zone) flame piece. Within the range of operating conditions investigated, the conjugate heat exchange with the bluff-body had no impact on the flame blow-off.

1. Introduction

In practical combustors, the inlet velocity of the premixed reactants are typically much higher than the unstretched adiabatic laminar burning velocity of the mixture. Bluff-bodies are often used to furnish the necessary mechanism for flame stabilization and continuous burning in such combustors. They provide a low-velocity region for the aerodynamic anchoring of the flame. There is often significant flame–wall interactions due to the conjugate heat exchange between the hot products and the nearby heat conducting bluff-body. In these systems, the length scales vary from the meter-scale combustor geometric details to the thin sub-millimeter-scale flame fronts. The time scales span the slow conjugate heat exchange processes and the rapid radicals' diffusion and reaction phenomena. In our recent work in [1], we developed a numerical method to accurately capture these wide spectra of spatial and temporal scales using an operator-split projection algorithm (for the multiple time-scales) coupled with a block-structured adaptive mesh refinement (SAMR) framework (for the multiple length-scales) and immersed boundary formalism (to incorporate the flame–wall interaction). When coupled with a detailed chemical kinetics mechanism, fully-resolved simulations using this tool can provide an insight into the complex underlying mechanisms of fundamental processes like flame stabilization and blow-off.

Blow-off of bluff-body stabilized premixed flames has been widely investigated in the literature, primarily using experiments due to the large computational expense involved. The impact of global chemical and aerodynamic parameters has been analyzed, with the earliest investigations reported in [2–5]. In these studies, the role of the bluff-body geometry, inflow velocity of the premixed reactants, and various other operating conditions on blow-off were analyzed. Typical blow-off curves were reported in the form of a plot of the maximum inlet reactant velocity for which the flame is stable at different equivalence ratios. Many phenomenological explanations were proposed based on the observed data. It was hypothesized that the flame blows off when the heat demand by

---

* Corresponding author.

http://dx.doi.org/10.1016/j.combustflame.2014.10.017

Nomenclature

Roman

c_{fh}	heat capacity of the bluff-body
d	width of the bluff-body
H	width of the channel
$\mathcal{L}$	Markstein length
n	flame normal directed towards the reactants
S	flame displacement speed
S_u^0	unstretched adiabatic flame displacement speed
t	time
T	temperature
T_u	temperature of the unburnt reactants
T_b	temperature of the burnt gas
U_{in}	average velocity of the incoming reactants
$\mathbf{v}$	velocity vector
u	velocity in the x-direction
v	velocity in the y-direction
v_n	velocity normal to the upstream Ref. location of 1% CH_4 consumption
Y_k	mass-fraction of the species k

Greek

δ_T	thermal thickness of the flame
$\alpha_{mix,u}$	thermal diffusivity of the unburnt reactants
ρ_{fh}	density of the bluff-body
λ_{fh}	thermal conductivity of the bluff-body
ϕ	equivalence ratio of the mixture
κ	flame stretch
κ_s	strain rate contribution to flame stretch
κ_c	curvature contribution to flame stretch

Non-dimensional numbers

Da	Damköhler number
Le	Lewis number
Ma	Markstein number
Re_d	Reynolds number based on d

the combustible stream in the shear layer for ignition exceeds the heat received by the recirculation zone [4,6]. Longwell et al. [3] proposed that blow-off occurs when the mass transfer of fresh reactants into the recirculation zone (which is viewed as a perfectly well-stirred reactor) and the rate of its consumption (equivalently the rate of burning) is not balanced. A similar idea was proposed in [2,7], suggesting that blow-off is caused by the imbalance between the heat supplied to the fresh reactants from the recirculation zone and the heat released by the reaction. Shanbhogue et al. [8] comprehensively reviewed the blow-off dynamics of the bluff-body stabilized flames at various Reynolds numbers. They demonstrated that the Damköhler number, based on various definitions discussed in Section 3.5, correlates very well to the experimentally observed data and essentially encapsulates the physics governing blow-off. Recent high-speed laser diagnostics based experimental investigations of turbulent bluff-body flames showed that extreme stretch rate in the shear layer results in local flame sheet extinction, which is a precursor to blow-off [9,10]. However, laminar flame blow-off mechanism cannot be explained from these investigations. The simulations discussed in this paper did not show any local extinction in the shear layer during blow-off.

Williams et al. [2] and Russi et al. [11] studied the impact of the flame-holder temperature on flame stabilization. They concluded that the conjugate heat exchange impacts the blowout limits in turbulent flames: heating/cooling the flame-holder decreases/increases the blowout tendency thus widening/shrinking the stability limit. However, Russi et al. [11] also demonstrated that the flame-holder temperature plays a weak role in the blow-off for low Reynolds number flow. Our recent experimental investigation in [12] revealed that the conjugate heat exchange with a backward-facing step in a combustor can significantly modify, or sometimes even suppress, the onset of the combustion instability depending on the operating conditions. A more thermally conductive steel step was reported to be more susceptible to the self-sustained oscillations than a less thermally conductive ceramic step.

Direct numerical simulations (DNS) often employ artificial flame anchoring conditions such as a high temperature hot-spot [13], isothermal flame-holders [14] or hot combustion products co-flowing with reactants at the inlet used in the slot-burner simulations in [15]. As a result, most DNS investigations are limited to the flow-field far away from the anchoring region. The impact of this assumption on numerical blow-off investigations is unclear. In this paper, we address the role of flame–wall interaction on bluff-body flame blow-off. Its impact on flame-anchoring was investigated in [16]. It was further shown to have a significant impact in determining the dynamic response of such flames to harmonic perturbations in [17]. We also elucidated the stabilization and blow-off mechanism of laminar premixed flames stabilized on a perforated-plate and highlighted the coupled role of curvature and local heat loss to the plate surface in [18]. Perforated-plate stabilized flame anchors at a finite standoff distance away from the plate, thereby impacting the plate temperature depending on the conjugate heat exchange. Blow-off was shown to occur when the flame-base ceases to satisfy a "dynamic stability criterion" that depends on the relative magnitudes of the flame displacement speed and the aerodynamic flow speed gradients at the location of the flame. In this paper we discuss this criterion in the context of bluff-body stabilized premixed flame.

Although a large body of literature exists on bluff-body flame blow-off, its underlying physics is still unclear. Experimental studies pose significant challenges due to the harsh environment, limited optical access and often inadequate field data. In almost all of the experimental investigations discussed above, a flow-based timescale (such as heat transfer rate, mass transfer rate, residence time in the recirculation zone) was compared to a chemical timescale (such as that of the burning rate, ignition, extinction). These hypotheses were based on the observed data correlation and thus lack a physical portrait of the local blow-off mechanism. Our objective is to use fully-resolved numerical simulations to examine the underlying physics and show a local sequence of events that leads to blow-off. We investigate the location and the condition at which blow-off is initiated. We focus on laminar flames only, thereby decoupling the additional complexities of flow unsteadiness and vortex shedding associated with turbulent flames.

This paper is organized as follows: we summarize the governing equations and the numerical method in Section 2. We present the simulations and propose a physical mechanism for blow-off in Section 3. The role of the conjugate heat exchange is also discussed. The conclusions are presented in Section 5.

2. Governing equations and numerical methodology

At the low-Mach number limit, the continuity, momentum and scalar equations are written in compact form as