Combustion and Flame 162 (2015) 2937–2953

Contents lists available at ScienceDirect

Combustion and Flame

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

Distributed reactions in highly turbulent premixed methane/air flames Part I. Flame structure characterization

Bo Zhou [a], Christian Brackmann [a], Qing Li [b], Zhenkan Wang [a], Per Petersson [a], Zhongshan Li [a,*], Marcus Aldén [a], Xue-song Bai [b]

[a] *Division of Combustion Physics, Lund University, P.O. Box 118, S221 00 Lund, Sweden*
[b] *Department of Energy Science, Lund University, P.O. Box 118, S221 00 Lund, Sweden*

ARTICLE INFO

Article history:
Received 20 October 2014
Received in revised form 19 December 2014
Accepted 22 December 2014
Available online 16 March 2015

Keywords:
PLIF
Distributed reaction zone regime
Turbulent premixed flames
LDV
Flame/turbulence interaction
Borghi diagram

ABSTRACT

Simultaneous planar laser-induced fluorescence (PLIF) measurements of a series of reactive scalars and Rayleigh scattering measurements of temperature, i.e. $CH/CH_2O/OH$, $HCO/CH_2O/OH$ and $T/CH_2O/OH$, and laser Doppler anemometry (LDA) measurements are carried out to characterize the flame/turbulence interaction in various regimes of turbulent combustion, including the laminar flamelet regime, the thin reaction zone (TRZ) regime, and the distributed reaction zone (DRZ) regime. A series of turbulent premixed methane/air jet flames with different jet speeds and equivalence ratios are studied. The jet Reynolds number ranges from 6000 to 40,000 and the Karlovitz number (*Ka*) of the studied flames varies from 25 to 1470. It is shown that in the TRZ regime CH/HCO layer remain thin but the layer of CH_2O and temperature gradient are broadened owing to the rapid turbulence transport. In the DRZ regime the CH and HCO layers are also broadened owing to the rapid transport of reactive species such as OH radicals from the high temperature regions where these radicals are formed to the low temperature region. In the DRZ regime CH and HCO are found to coexist with OH or CH_2O owing to the rapid turbulence eddy interaction, which differs fundamentally from that in the TRZ regime and the laminar flamelet regime. For the present investigated flames, the temperature range for the distributed reaction to occur is found to be between 1100 K and 1500 K. It is shown that the structures of flames in different regimes can affect the turbulence field differently. In the DRZ regime the temperature gradient is lower than that in the laminar flamelet and the TRZ regimes, which results in a lower peak of turbulence intensity owing to the retarded velocity gradient across the flames and thereby a lower rate of turbulence production.

© 2015 The Combustion Institute. Published by Elsevier Inc. All rights reserved.

1. Introduction

Combustion in most practical applications operates at highly turbulent conditions. The interaction between turbulence and chemical reactions has been one of the most important research subjects in the combustion community over the last a few decades. For premixed turbulent combustion, several authors have proposed a regime diagram to delimit the various combustion regimes on the basis of scaling analysis, e.g. [1–3]; a review on the regime diagram of turbulent premixed flames can be found in Lipatnikov and Chomiak [4] where a list of different versions of the regime diagram is given. In the regime diagram modified by Peters [3], a non-dimensional parameter, the Karlovitz number (*Ka*), was introduced to classify the regimes. The *Ka* is defined as the ratio of the time scale of the chemical reactions to the smallest time scale of turbulence (the Kolmogorov time scale). In the wrinkled and corrugated flamelet regimes, it is argued that the thickness of flame front (δ_L) is thinner than the Kolmogorov length scale (η). As such, turbulence can only wrinkle the flame front so that the instantaneous flame front can be modeled locally as a laminar flamelet. As turbulence becomes stronger, i.e. η becomes smaller, the thin reaction zone (TRZ) regime is approached, in which η is smaller than the flame thickness (δ_L) but still larger than the length scale of the thin fuel-consumption layer (known as the inner layer that has a thickness δ_r on the order of one tenth of δ_L [5]). The Karlovitz number in the thin reaction zone regime is therefore in the range $1 < Ka < 100$. In this regime, the preheat zone can be distorted and broadened by small eddies while the inner layer of the reaction zone remains thin and intact. The aforementioned regimes have the important common characteristic that the major heat release is confined to a thin reaction zone that separates the unburned reactants from the burned products and the internal

---

* Corresponding author.
E-mail address: Zhongshan.li@forbrf.lth.se (Z. Li).

http://dx.doi.org/10.1016/j.combustflame.2014.12.021
0010-2180/© 2015 The Combustion Institute. Published by Elsevier Inc. All rights reserved.

structure of the thin reaction zone is barely distorted by turbulence eddies. This leads to the "flamelet" concept being widely applicable as validated by experimental observations [6–11] and direct numerical simulations (DNS) [12,13].

However, a spontaneous question is that to which extent the flamelet concept will still be valid as the Kolmogorov scale becomes smaller than δ_r (i.e. $Ka > 100$) so that small eddies could distort and consequently broaden the reaction zone [14,15]. Evidence from experiments [16–19] as well as numerical simulations [20,21] has shed light on the limit of the flamelet concept. Moreover, it is also highly questioned whether the flame can be sustained at $Ka > 100$ [4,22], since it has been observed that the flame may be shredded [23] or quenched [24–26] before being broadened due to high levels of stretch and heat loss exerted by intense turbulence. Due to the aforementioned reasons, the regime with $Ka > 100$ is referred to as the distributed or broken reaction zone regime, depending on whether a flame can be sustained.

Recently, we have experimentally observed a broad spatial distribution of short-lived CH and HCO radicals in flames established on a piloted jet burner (LUPJ, abbreviated from Lund University Piloted Jet burner) [27], indicating distributed reactions. In the LUPJ, a laminar pilot coflow flame is used to prevent the turbulent jet flames from quenching, thus allowing for well-stabilized jet flames with *Ka* significantly higher than one hundred. Similar burners have also been employed by other groups to generate high *Ka* flames [18,28]. It can be concluded that flames like the ones employed in the present study do not necessarily extinguish at high *Ka* if properly protected by a hot coflow. For this reason, the present paper prefers to use the term "distributed reaction zone (DRZ)" regime instead of the "broken reaction zone" regime.

Theoretical predictions of combustion in the DRZ regime have been presented in several pioneering works [29–31]. In short, it has been characterized by: (1) the elimination of the sharp interfaces between the unburnt and the products owing to the rapid turbulence-dominated mixing; (2) the relatively broadened heat-release region with reduced local burning rate; and consequently (3) the reduced maximum flame temperature and homogenized temperature field. The first feature calls for a revision of the current flamelet combustion models for numerical simulations of turbulent premixed combustion. There is no obvious flamelet generated manifolds, and the concepts of displacement speeds of the flame fronts and the flame surface density may no longer be valid. Finite rate chemistry may have to be used in the numerical simulations, which requires greater computer resources for the multi-scale physical and chemical processes involved. The second and third features could be of benefit to reduce the thermal NO_x emission as its production is strongly temperature dependent. To our knowledge, the DRZ regime is fairly unexplored in the existing literature [32,33]. The need to systematically investigate the basic structures and dynamics of premixed flames in the DRZ regime is clear, and examining the similarity/difference among the flames in the various regimes is one of the present focuses.

The present work is an extension of our recent work on the DRZ regime combustion [27]. Here, a wider range of flames with varying degree of turbulence and equivalence ratios are considered. Reactive scalars (i.e. OH, CH_2O, CH and HCO) and temperature (T) have been captured instantaneously by three series of simultaneous imaging measurements which include planar laser-induced fluorescence (PLIF) of OH/CH_2O in combination alternatively with CH PLIF, HCO PLIF or planar Rayleigh scattering temperature measurements. For the T/CH_2O/OH measurements, quantifications of CH_2O and OH concentrations have been made based on data from the corresponding laminar flames and the instantaneous temperature field. In addition, the flow fields of the flames were measured using laser Doppler anemometry (LDA). One goal of this work is to clarify the dependences of reactive scalars on the jet speed (U_0) and equivalence ratio (Φ). The other goal is to obtain a dataset from the statistical analysis of the PLIF, the Rayleigh thermometry and the LDA measurements for model development and validation in the DRZ regime.

2. Experimental details

2.1. Laser diagnostics

The LUPJ burner consists of a porous sintered-brass plate (61 mm in diameter) with a center jet 1.5 mm (d) in diameter. A flat laminar CH_4/air flame with the exit flow velocity of 0.3 m/s and $\Phi = 0.9$ was stabilized on the porous-plug surface. Details about the investigated flames will be given in Section 2.2. Other details about the burner configuration are referred to Ref. [34].

The experimental system for simultaneous multi-scalar two dimensional imaging has been described in detail in our previous work [27] and only a brief description is given here. For Rayleigh scattering thermometry, an *s*-polarized 355-nm Nd:YAG laser was employed together with a bandpass filter (355 ± 5 nm) for detection. Formaldehyde (CH_2O) was excited using the same laser, and the signal was detected at wavelengths above 400 nm. The OH radicals were excited at the $Q_1(8)$ transition in the $A^2\Sigma^+$–$X^2\Pi$ (1-0) band, and the off-resonance fluorescence centered at 309 nm was detected. An alexandrite laser was employed for the excitation of CH at 387 nm and HCO at 259 nm, respectively, following the excitation–detection strategies detailed in Refs. [34,35] with special care to ensure an interference-free detection [34–36]. The thickness of the combined laser sheets was measured to be 100 μm and an imaging spatial resolution for PLIF and Rayleigh measurements of around $70 \times 70\ \mu m^2$ was determined from the finest resolvable pattern on a resolution target (USAF-1951). Other experimental parameters and further information about the imaging qualities and the signal-to-noise ratios (SNR) of measured scalars can be found in Ref. [27]. Based on species concentrations estimated from CHEMKIN simulations (see Section 4.2 for details) and the achieved experimental SNRs, the detection limits are evaluated to be ~100 ppm for OH, 40 ppm for CH_2O, 3 ppm for HCO and 0.1 ppm for CH.

To measure the axial velocity component and its fluctuations a calibrated LDA system (Dantec, Flow Explorer DPSS & BSA F80 processor unit) was employed. A diode pumped solid state laser is used to generate beams at 532 nm with average powers of 300 mW. The laser beam is split into two beams, one of which is shifted in frequency with 80 MHz enabling detection of instantaneous stagnation and reversal flows. The incident laser beams were focused using a 300 mm lens above the center of the jet exit, giving a physical ellipsoidal probe volume of 80 (width) × 80 (height) × 700 (length) μm^3. This optical setup allows for the detection of velocities up to around 300 m/s. The signal, burst of scattered light from seeding particles crossing the fringes, is collected in a back-scatter mode with the signal receiving optics incorporated in the LDA probe. The data acquisition was performed at temporal equidistant intervals with a sampling interval (typically 100 μs) of at least twice the estimated integral timescale of the investigated jet conditions. This approach was used to avoid over-sampling the velocity information, to eliminate velocity bias and also to reduce bias effects due to a non-uniform seeding density in the jet and the coflow. The maximum number of independent acquired samples was set to 10^4. A fluidized-bed seeder was used to seed 0.5-μm diameter Al_2O_3 particles into the main jet air flow which was then mixed with the fuel stream before entering the burner. The LDA measurements have been focused on the stoichiometric turbulent flames. Lean flames ($\Phi = 0.4$) with jet speeds of 66, 330 and 418 m/s as well as a non-reacting case with the jet speed of 165 m/s were also performed for reference. Pointwise LDA measurements were started from 4 mm up to 120 mm height above the burner surface (x) with a 3 mm interval between

Download English Version:

https://daneshyari.com/en/article/166262

Download Persian Version:

https://daneshyari.com/article/166262

Daneshyari.com