ARTICLE IN PRESS

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ScienceDirect

Proceedings of the Combustion Institute xxx (2014) xxx–xxx

Proceedings of the Combustion Institute

www.elsevier.com/locate/proci

Investigation of pressure effects on the small scale wrinkling of turbulent premixed Bunsen flames

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Abstract

High pressure turbulent premixed flames have been significantly studied in the past decade. The eloquent flame images obtained under high pressure conditions attest the large changes in flame front wrinkling enhanced by the pressure increase. Among the explanation attempts, pressure was assumed to promote Darrieus–Landau (DL) instabilities. More recently the role of the laminar flame thickness was also identified as a key parameter for the flame/turbulence interactions. The objective of the current study is to contribute to this debate by isolating the effects of the suspected parameters. To do so, turbulent methane/air flames are investigated in a high pressure combustion test facility. A multi-grid turbulence promoter system has been developed and implemented to obtain a more intense, isotropic and homogeneous turbulence at the burner exit. The pressure range is 0.1–0.4 MPa, and the mixture composition is varied between ER = 0.7 and ER = 1.0. Instantaneous flame images have been collected using Mie scattering tomography and exploited to analyze flame–turbulence interactions under controlled conditions. Flame and turbulence parameters have been independently varied under DL instability free conditions to isolate the effect of the laminar flame thickness and that of the small scale turbulence eddies. The stretching of the turbulence energy spectrum towards smaller turbulent length scales is identified as the main reason for the enhanced flame front wrinkling under high pressure flame conditions, together with the reduction of the laminar flame thickness. The Taylor micro-scale appears to be the regulating turbulence scale for flame–turbulence interactions.

Keywords: Turbulent premixed flames; Pressure effects; Darrieus–Landau instability; Laminar flame thickness; Taylor length scale

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1. Introduction

Combustion pressures are being progressively increased to answer the requirements concerning thermal efficiency improvement and reduction of overall combustion chamber dimensions. High-

http://dx.doi.org/10.1016/j.proci.2014.06.036

1540-7489/

pressure turbulent premixed combustion is widely used for high-load practical combustion systems, such as spark ignition (SI) engines and lean premixed flame-type gas turbine combustors.

High pressure turbulent premixed flames appear globally very different compared to atmospheric pressure flames due to the emergence of very small scale structures. This global flame surface enhancement results in flame propagation velocity increase and higher heat release rates. This observation was made experimentally by several groups on either stationary burners [1–8] or turbulent expanding flames [9–12]. In his book, Lipatnikov [13] gives an overview of empirical parameterizations which can be found for turbulent burning velocity modeling. The short list of controlling parameters commonly used (rms velocity, integral length scale, flame velocity and thickness) is completed with several other parameters including dimensionless numbers (i.e., Damköhler, turbulent Reynolds, Karlovitz and Lewis numbers).

When pressure is increased, both flame and turbulence characteristics are affected. For all hydrocarbon fuels, laminar burning velocities and flame thicknesses are reduced when pressure rises. The reduction of the flame thickness promotes the hydrodynamic instability through the modification of the jump conditions. Moreover, the flame thickness can be interpreted as a cut-off wavelength of the turbulence spectrum for flame–turbulence interactions. Concerning turbulence characteristics, integral length scales remain almost constant and smaller scales are reduced with pressure. The integral length scale is an inherent parameter of the experimental setup and can be related to geometrical characteristics such as the blade pitch angle of the impellers for turbulent spherically expanding flames [14,15] or the turbulence grid mesh for stationary burners [7,16,17]. As pressure increases, the turbulence energy spectra show that the high frequencies have more energy [15], meaning that the pressure increase generates smaller time scale turbulent structures and consequently smaller turbulent length scales.

As flame and turbulence characteristics are both changed when pressure increases, the identification of the parameter(s) controlling the higher wrinkling of the flame front is delicate. For example, this behavior can be explained by the increased presence of highly fluctuating, small-scale turbulent motions interacting with the flame front but also by the increased instability of the flame itself. In the studies of Kobayashi et al. [18] and Liu et al. [19], the flame front structure modifications with the increase of pressure were mainly attributed to the Darrieus–Landau (DL) instability. This was recently challenged by Chaudhuri et al. [12] who emphasized the importance of the laminar flame thickness reduction.

The objective of the present paper is to investigate the mechanisms of high pressure turbulent premixed flame wrinkling and to identify the parameter(s) to be taken into account to correctly predict the turbulent burning velocity under high pressure conditions.

A Bunsen burner configuration equipped with a multi-scale turbulence generator is used. Several premixed methane/air flames with varying equivalence ratio and pressure conditions are explored to isolate progressively the effects of different parameters (i.e., laminar burning velocity, laminar flame thickness, and turbulence characteristics). After discussing the minor role of DL instability in our experimental conditions, the role of the laminar flame thickness on the flame wrinkling structure is investigated. We also discuss the role of the different turbulent scales when the laminar flame thickness is kept constant.

2. Experimental set-up and procedure

Experiments are performed using a high pressure combustion test facility operating at pressures up to 0.5 MPa. A nozzle type burner with an exit section diameter of 25 mm is used and a Bunsen-type turbulent premixed flame is stabilized with the help of a premixed methane/air pilot flame. The bulk flow velocity (U_{mean}) is kept constant around 3.5 m/s for all the conditions. More details of the facility are described elsewhere [7,20,21].

2.1. Multi-grid turbulence generator and turbulent characteristics determination

A multi-grid system has been developed and implemented to obtain a more intense, isotropic and homogeneous turbulence at the burner exit. Multi-scale grid generated turbulence has been recently investigated in the literature [22,23]. The main disadvantage of standard single grid generated turbulence lies in its inability to reach high turbulence intensities and therefore its use is restricted to moderate Taylor scale based Reynolds numbers.

The multiscale grid device is composed of three successive perforated plates of progressively increasing hole diameter and mesh size (1st = 1.55 mm (hole) and 2 mm (mesh); 2nd = 3.44 mm and 5 mm; 3rd = 7.5 mm and 12.5 mm) which leads to increasing blockage ratios (1st = 0.46, 2nd = 0.57 and 3rd = 0.67). The third grid is located 60.5 mm upstream of the burner exit, the second is placed 17 mm below the third and the first one 7 mm below the second. These locations have been chosen following the rules defined by Mazellier et al. [23]. The multi-scale grid is dedicated to mimic the turbulence cascade process as each grid parameters are designed to enhance a

Please cite this article in press as: R. Fragner et al., *Proc. Combust. Inst.* (2014), http://dx.doi.org/10.1016/j.proci.2014.06.036