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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 0.1–0.4MPa, 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.

Introduction

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

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 [1, 2] or the turbulence grid mesh for stationary burners [3-5]. As pressure increases, the turbulence energy spectra show that the high frequencies have more energy [2], 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. [6] and Liu et al. [7], 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. [8] who emphasized the importance of the laminar flame thickness reduction.

Approach

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. 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 flame thickness, and turbulence characteristics).

Experiments are performed using a high pressure combustion test facility operating at pressures up to 0.5MPa. 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 3.5m/s for all the conditions.

A multi-grid system has been developed and implemented to obtain a more intense, isotropic and homogeneous turbulence at the burner exit. In comparison with the standard single grid system, the turbulence intensity of the multi scale device is doubled (around 10%) in the homogenous zone. In addition, small turbulent scales are smaller and contain more energy.

An Nd–YAG laser and a CCD camera (TSI PIV CAM 10-30, 1016x1008 pixels^2) are used for Mie scattering visualizations. The local flame front curvature, h, is calculated for each pixel along the flame edge. By convention, h is positive when the flame front is convex to reactants. Binarized images are summed and averaged to produce the average reaction progress variable <c> maps. The <c> contours obtained from them represent the probability of the instantaneous flame front being at a given location within the average flame brush. The location of the mean progress variable at <c> =0.05 is considered to be the inner surface of the flame brush [9]. The turbulent burning velocities reported in this paper are determined using the conventional flame-angle method based on <c>=0.05 [10].

Results and discussion

For all the conditions presently investigated, u' is constant and the non-dimensional turbulence intensity remains lower than 4, corresponding to a Karlovitz number lower than 2. As reported by Yuen et al. [11], the flamelet hypothesis is still valid for these conditions. As a result, we assume that even if smaller and more intense turbulent scales are generated when pressure is increased, they are not energetic enough to modify to inner structure of the instantaneous flame front whose thickness is reduced by pressure effect.

Recently, Chaudhuri et al. [8] proposed to unify the turbulent flame speed data from expanding flames and from Bunsen flames using the root square of a modified turbulent Reynolds number: $[(u'/S_L)*(R/\delta_L)]^{(1/2)}$. The length scale R corresponds to the average flame radius in the case of spherical flames and to the burner diameter for Bunsen flames. When all the parameters except the laminar flame thickness are constant (u', S_L and R), the combustion intensity varies linearly with the square root of the laminar flame thickness. This strongly suggests that the laminar flame thickness has a non-negligible effect on the flame front wrinkling.

The laminar flame thickness corresponds to a very short distance where the important temperature jump considerably modifies the mixture viscosity and density. As a consequence, the small turbulent eddies approaching this zone are rapidly dissipated if they are not energetic enough [12]. Following this approach, it appears that the laminar flame thickness may be considered as a cut-off wavelength for flame. This was illustrated in Poludnenko et Oran [13] where the thermal thickness was introduced in the energy spectra to identify the turbulent scales able to wrinkle the flame front. To check the reliability of this conjecture, curvature distributions of three different flames presenting different flame thicknesses are determined. When the flame thickness is reduced, the distribution is broadened showing higher probabilities for larger curvatures, indicating the enhancement of smaller scale flame front wrinkling. Following Chaudhuri et al. [8], we have multiplied the curvature by a non dimensional flame thickness to the power ½. With this scaling, the three distributions superimpose correctly indicating that the laminar flame thickness directly impacts the flame front geometry and needs to be considered in turbulent burning velocity correlations. For smaller flame thicknesses, smaller eddies are able to wrinkle it and increase the flame surface area.

Increasing pressure modifies notably the small turbulent scales. Lachaux et al. [4] have shown that the Taylor micro-scale λ varies as $P^{-1/2}$ and the Kolmogorov length scale η as $P^{-3/4}$. This results in stretching the spectrum towards higher wavelengths (or smaller scales). Increasing pressure increases the Reynolds number and the range of turbulent scales in the flow. It is important to recall here that u' (the total turbulent energy in the axial component) is unchanged with pressure; therefore increasing the pressure distributes more energy to the small scales (for constant total turbulence energy the turbulent Reynolds number based on the integral length scale increases because of the decrease of the kinematic viscosity with pressure).

An important question is whether these turbulence structural modifications impact the flame front wrinkling and if yes, is there a scale which dominates these flame/turbulence interactions? To answer these questions, three different experimental conditions have been selected by varying the pressure but keeping almost constant the laminar flame thickness. To do so, the equivalence ratio was adjusted for each pressure condition. With this approach, we can reasonably expect that the observed differences are only imputable to the modifications in the structure of turbulence

When pressure is increased, the distributions are broadened with higher probabilities for larger curvatures indicating the generation of smaller flame wrinkling. Then the distributions are multiplied by a non dimensional Taylor length scale to account for the decrease of this scale when pressure rises. This scaling leads to an almost perfect superposition of the curvature PDFs.

The above results give some new insight on the effects of pressure on flame wrinkling and more generally on flame-turbulence interactions. When the laminar flame thickness is reduced (with all other parameters kept constant), small scale flame wrinkling augments. When the laminar flame thickness is kept constant, increasing the turbulent energy content in the small scale also increases flame wrinkling. We have shown that increasing the pressure reduces the laminar flame thickness and increases the turbulent energy content in the small scales. The Taylor micro-scale appears as the regulating scale for flame front turbulence interactions. This is reasonable in the sense that this scale represents the average size of eddies active in the spectral cascade process and having sufficient energy to interact with the flame front and wrinkle it. Our attempt to scale the flame front curvature PDFs by the Kolmogorov length scale was unsuccessful. This indicates that such small scales do not possess enough energy to wrinkle the flame front especially when the laminar flame thickness is of the same order of magnitude as the Kolmogorov length scale. On the other hand, even if the smallest scales do not penetrate the flame thickness, robust enough intermediate sized small scales represented by the Taylor micro-scale are able to contribute to the wrinkling of the flame front especially when the laminar flame thickness is reduced. Therefore the ratio between the Taylor micro-scale and the laminar flame thickness should be an important regulating parameter for flame turbulence interactions and the generation of small scale flame surface elements.

Conclusions

Instantaneous images of turbulent methane/air premixed flames are obtained in a high-pressure chamber using Bunsen-type burner stabilized flames and Mie scattering tomography. A multi-scale turbulence generator has been implemented to obtain a more intense, isotropic and homogeneous turbulence at the burner exit. The explored pressure range is 0.1-0.4 MPa, and the mixture composition is varied between ER=0.7 and ER=1.0.

The objective was to analyze the mechanisms responsible of the premixed flame front small scale wrinkling observed under high pressure conditions. The current contribution emphasizes the importance of laminar flame thickness in flame/turbulence interactions and the major role played by the Taylor length scale largely affected by a pressure rise.

The main conclusions of the paper are:

- Pressure increase results in stretching the energy spectrum towards higher wavenumbers.
- Under present experimental conditions, the increase in combustion intensity (S_T/S_L) observed when pressure is increased is not due to Darrieus-Landau instability. This conclusion is confirmed by the modified combustion diagram recently proposed by Chaudhuri et al. [14] and also by the laminar flame experiments we performed showing that the present flame conditions are free of DL instability.
- For constant turbulence conditions, differences in curvature distributions are observed when varying the laminar flame thickness. For a smaller flame thickness, the distributions are broadened with higher probabilities for larger curvatures, indicating the enhancement of smaller scale flame front wrinkling. Moreover, a scaling of the curvature distribution with the laminar flame thickness to the power ½ is found.
- When pressure is increased, keeping constant the laminar flame thickness, the curvature distributions also broaden with higher probabilities of larger curvatures indicating a stronger interaction between the small turbulent scales and the flame front. Moreover, the Taylor micro-length scale is found to be representative of the scales interacting with the instantaneous flame fronts. This scale should therefore be taken into account to correctly predict the turbulent burning velocity.

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