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Flame front analysis of high-pressure turbulent lean premixed methane–air flames

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Abstract

An experimental study on lean turbulent premixed methane–air flames at high pressure is conducted by using a turbulent Bunsen flame configuration. A single equivalence ratio flame at $\Phi = 0.6$ is explored for pressures ranging from atmospheric pressure to 0.9 MPa. LDA measurements of the cold flow indicate that turbulence intensities and the integral length scale are not sensitive to pressure. Due to the decreased kinematic viscosity with increasing pressure, the turbulent Reynolds numbers increase, and isotropic turbulence scaling relations indicate a large decrease of the smallest turbulence scales. Available experimental results and PREMIX code computations indicate a decrease in laminar flame propagation velocities with increasing pressure, essentially between the atmospheric pressure and 0.5 MPa. The u'/S_L ratio increases therefore accordingly. Instantaneous flame images are obtained by Mie scattering tomography. The images and their analysis show that pressure increase generates small scale flame structures. In an attempt to generalize these results, the variance of the flamelet curvatures, the standard deviation of the flamelet orientation angle, and the flamelet crossing lengths have been plotted against $Re_t^{1/2}$ which is proportional to the ratio between the integral and Taylor length scales, and which increases with pressure. These three parameters vary linearly with the ratio between large and small turbulence scales and clearly indicate the strong effect of this parameter on premixed turbulent flame dynamics and structure. An obvious consequence is the increase in flame surface density and hence burning rate with pressure, as confirmed by its direct determination from 2D tomographic images.
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Keywords: Turbulent; Pressure; Premixed; Scale; Wrinkled

1. Introduction

Many practical power production applications use premixed hydrocarbon–air combustion at elevated pressures. For these applications, thermal efficiency improvement, reduction of overall combustion chamber dimensions, and reduction of pollutant emissions are required more and more. Hence, combustion pressures are being progressively increased. For example, a pressure ratio approaching 40 is thought desirable for a modern gas turbine [1]. Few experimental studies are, however, available today for detailed high-pressure premixed turbulent flame characterization. Kobayashi et al. [2,3] used an axisymmetric

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Bunsen burner with perforated plates to generate turbulence and operated up to 3 MPa, maintaining constant ambient combustion chamber temperature by the addition of air. They report a decrease in the Kolmogorov length scale with increasing pressure but the integral length scales tend to stay constant. Schlieren images show smaller flame wrinkling scales when pressure rises. Lee et al. [4], with the same configuration, found that the flame surface density obtained by using the Bray Moss Libby (BML) model and planar laser induced fluorescence grows with pressure. Soika et al. [5] investigated a bluff-body stabilized flame up to 1.1 MPa and observed a broadening of the flame front curvature distribution as pressure rises, indicating that the flame front becomes strongly wrinkled, caused mainly by pressure enhanced small scale turbulence interactions and flame instabilities.

The primary objective of the present study was to characterize further high-pressure lean turbulent premixed flames by determining wrinkling scales, flame front curvature, and surface density. The ultimate goal was to propose a general understanding of the effects of high pressure on lean premixed turbulent flame dynamics. We first describe the burner, the combustion chamber, and the experimental conditions, and then present the primary diagnostics: laser Doppler anemometry and Mie scattering tomography. The results mainly concern the pressure effects on instantaneous and average flame properties. Laminar flame computations are used to determine reference values for laminar flame burning velocities and thicknesses. It is shown that the primary effects of pressure on the premixed flame structure can be correlated to changes in the range of turbulent scales in the reactant stream.

2. Experimental set-ups

A stainless steel cylindrical combustion chamber, inner diameter 300 mm, has been developed to enable experiments up to 1 MPa to be performed, Fig. 1. The chamber has two 600 mm high superposed vertical cylinders with four 100 mm diameter windows (glass or quartz) for optical diagnostics. The internal volume is approximately 80 L. Water flowing through the jacketed chamber walls cools the chamber. The centrally placed burner can traverse the chamber's vertical z-axis by a stepping motor with an accuracy of 0.1 mm. The internal walls are painted black with a laser light absorbing paint, resistant to temperature. The laser light traverses the combustion chamber through two opposite windows. The windows are electrically warmed to avoid water condensation, and a nitrogen flow dries the windows during measurements if necessary. The internal pressure is set manually; a pressure gauge and a thermocouple are used to check burned gas pressure and temperature. No pressure oscillations or any other confinement effects were observed.

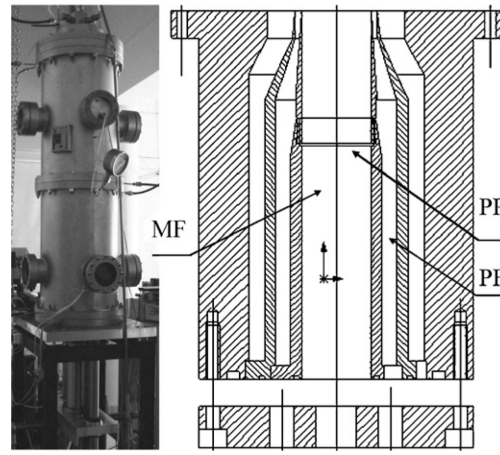

Fig. 1. Combustion chamber (left) and schematic view of the burner (right) PF, pilot flame annular channel; PP, perforated plate; and MF, main flame tube.

The burner, also in Fig. 1, is an axisymmetric Bunsen burner, fed by premixed methane–air. The internal burner diameter D is 25 mm, and its length is 230 mm. A perforated plate, blockage ratio 0.51, with 2.5 mm diameter holes in an hexagonal array, is located 50 mm upstream of the burner exit and generates the cold flow turbulence.

An annular laminar stoichiometric methane–air pilot flame stabilizes the main turbulent flame. The dry air, cleaned by a sub-micron filter and provided to the premixer by a 1.3 MPa compressor, and methane from compressed gas bottles, are controlled by regulated thermal mass flowmeters.

2.1. Mie scattering tomography

A 15 Hz pulsed Nd Yag laser (Spectra Physics GCR 130) at 532.5 nm is used for Mie scattering flame tomography. The pulse energy is 270 mJ. The laser beam passing through a 1000 mm focal length spherical lens and a 25.4 mm focal length cylindrical lens produces a light sheet 200 μm thick and approximately 90 mm high. The flow was seeded by olive oil droplets supplied by an atomizer. The mean droplet diameter was measured by phase Doppler anemometry at 4.3 μm. The Mie scattered light was collected at 90° to the sheet by a CCD camera (TSI PIV CAM 10-30, 1016×1008 pixels^2). The collection lens, focal length 50 mm, was equipped with an interference filter centered at 532 nm. The overall resolution was 0.11 mm/pixel. Laser Doppler Anemometry

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