Fuel 230 (2018) 274–281

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Pre-chamber ignition mechanism: Experiments and simulations on turbulent jet flame structure

P.M. Allison*, M. de Oliveira, A. Giusti, E. Mastorakos

Department of Engineering, University of Cambridge, Cambridge CB2 1PZ, UK

ARTICLE INFO

Keywords:
Turbulent jet
Ignition
Chemiluminescence
Quenching

ABSTRACT

This work investigates the effects of premixed combustion kinematics in pre-chamber volumes on the development of emitted hot jets from the igniter. The effects of fuel type, orifice diameter, and ignition location are evaluated experimentally, with high-speed OH* and CH* chemiluminescence imaging, and computationally with Large-Eddy Simulations (LES). The imaging experiments allowed for simultaneous viewing of combustion processes within a quartz chamber and of the developing jet flow. Results from these experiments provided insight on the temporal evolution of the jet relative to the growth of an ignited kernel within the chamber, as well as information on the emission or lack of emission of radical species from the chamber. Computational results provided data on the temporal behavior of the pressure within the chamber and profiles of the high velocity flow through the orifice. These results, combined, have shown that dependent on the strain rate and effective orifice size, local quenching of radical species at the orifice occurs which fundamentally change whether hot products, reactive layers, or both are present in the turbulent jet emission. The dynamic structure and composition of the turbulent jet controls its relevance as an effective ignition source.

1. Introduction

Ignition in large-scale natural gas internal engines may be difficult to achieve with standard electrical spark systems at high pressures and lean chamber mixtures. Ignition by hot turbulent jets from a pre-chamber igniter is proving to be advantageous for these types of combustion environments. These pre-chamber systems are composed of a small volume adjoined to the combustion cylinder. Within the pre-chamber, a standard electrical spark is used to ignite a fuel-air mixture controlled by separate fuel injection in the pre-chamber or the mixture that has entered from the main chamber during the compression stroke. Dependent on the mixture and chamber geometry, a combination of reacting and quenched species are injected into the main chamber by high-speed, hot turbulent jets emerging from small orifices that connect the main and pre-chamber volumes.

This process of ignition via emerging jets from a pre-chamber is denoted as "Turbulent Jet Ignition (TJI)" in literature and has been the focus of studies on fundamental and industrial devices at lab-scale and engine-relevant conditions. Toulson et al. [1] have provided a thorough review of pre-chamber systems as prescribed to engine-based applications. Studies conducted at industrial scales are difficult to image, however several fundamental works have investigated the jet development in simpler geometries. Yamaguchi et al. [2] investigated, in a separated pre-chamber and main chamber, the ignition and burning mechanisms of the main chamber mixture by a torch jet (orifice diameters between 4 and 14 mm). Recently, Biswas et al. [3,4] studied the ignition mechanisms of CH_4/air and H_2/air mixtures and two ignition mechanisms were identified as "jet ignition" and "flame ignition", respectively corresponding to jets consisting of hot combustion products and wrinkled turbulent flames, respectively. The idea of a critical global Damköhler number was introduced, as a limiting parameter that separates the ignition from a no-ignition regime.

Several other experimental studies have investigated pre-chamber ignition in full scale natural gas engines and rapid compression machines (RCM) for observation at elevated pressures. A joint experimental and computation effort by Roesthlisberger and Favrat [5,6] identified engine performance effects of varying pre-chamber orientation and orifice geometry within the cylinder. RCM studies [7–9] have focused on geometric effects on the ignition and flame spread within a main chamber. In particular, high speed imaging revealed the influences of orifice size and mixture composition on the jet dynamics.

The primary foci of these previous studies have been on pre-chamber mixture composition and geometry and their relation towards the ignition of some external volume or flow. In this sense, the physical application of the pre-chamber as an igniter has been of importance. However, little investigation has been placed on the fundamental

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* Corresponding author.
E-mail address: pma34@cam.ac.uk (P.M. Allison).

https://doi.org/10.1016/j.fuel.2018.05.005
Received 21 December 2017; Received in revised form 22 April 2018; Accepted 1 May 2018

nature of what occurs inside the pre-chamber and the evolution of the jet as a fluid dynamic feature independent of an external flammable mixture. This motivated a short preliminary study by Mastorakos et al. [10], which combined experimental and computational observations of flame propagation and turbulent jet emission from a small optically accessible quartz volume for a few operational conditions. The goal of that work was to focus on understanding the basic mechanism of turbulent jet formation from the chamber.

Given the previous findings, the aim of the current work was to further investigate fundamental turbulent jet dynamics. Compared to the preliminary study [10], this work has been expanded to consider new effects of fuel type, mixture composition, orifice size, and ignition location in the chamber. The current work experimentally and computationally evaluates, in a simple geometry with complete optical access to the pre-chamber, the temporal behavior and emission of the jet as correlated with the propagation of flames imaged within the pre-chamber. Particular emphasis was placed on the presence of OH^* and CH^* radical chemiluminescence emission from the jet to evaluate quenching of the reactive flow due to thermal losses and strain through the orifices. New large eddy simulations (LES) of the same configuration studied experimentally have also been performed to provide insight on chamber pressure and velocity through the orifice and how these may relate to quenching in the jet. The structural nature of the jet composition as a combination of fresh mixture, reactive layers, and hot products is essential to the performance of pre-chambers as ignition sources. These combined experimental and computational efforts provide further fundamental understanding of the dynamic and regimental behavior of pre-chamber ignition processes.

2. Experimental and numerical methods

The pre-chamber apparatus used is shown in Fig. 1. It consists of a quartz cylinder with an inner diameter of 32 mm and a length of 32 mm, constrained at both ends with flat, 1.5 mm thick steel plates. This volume forms the "pre-chamber". The quartz cylinder allows for complete optical access to the pre-chamber and the ability to image the evolution of the confined flame growth. The baseplate has a series of sharp-edged holes which are used as the exit orifice. These orifices allow for the selection of chamber exits with diameters of 1.5 mm, 3 mm or 6 mm. The other plate has an opening fit with a solenoid valve, which is used for filling the pre-chamber with the mixture to be ignited. In the images, an apparent 4 mm gap between the bottom of the chamber and beginning of the jet is seen. This viewing blockage is due to the combined thicknesses of the end plate and sealing gasket. The premixed equivalence ratio of the mixture inside is varied between 0.9 and 1.2 for methane-air and ethylene-air mixtures. The fluid into which the jet emerges is air at ambient conditions. Table 1 provides the operating conditions and geometric configurations over which experiments were conducted.

Ignition is provided by a spark created by a focused 532 nm laser beam from a Continuum Surelite II Nd:YAG laser at 50 mJ/pulse. Laser ignition allows for precise control of the spark location and for this fundamental study removes any physical obstructions to the kernel growth due to ignition hardware. A similar strategy was employed for pre-chamber studies by Joshi et al. [11]. The laser is focused at two different centerline locations within the chamber; 16 mm from the orifice exit (center of the chamber) and 30 mm from the orifice exit at the mixture inlet (top of the chamber). For ignition at the top of the chamber, the beam is focused by a 100 mm focal length through the orifice and impinges on the pre-chamber top endplate. The laser beam is delivered from a 50 mm focal length lens for the chamber-centered ignition location through the side of the quartz cylinder. This creates the ignition basis kernel with a toroidal shape characteristic of laser ignited mixtures [12,13]. Ignition at the top of the chamber does not create a toroidal kernel. It appears that the spark interaction with the wall creates a hemispherical ignition kernel which propagates toward the orifice.

Table 1
Experimental test conditions and evidence of radical presence in the jet.

Fuel	Orifice Diameter [mm]	Ignition Location	Equivalence Ratio	Jet OH^*	Jet CH^*
Methane	1.5	Top	0.9, 1.0, 1.2	✓ (low signal)	✗
	3	Top	0.9, 1.0, 1.2	✓	✗
	6	Top	0.9, 1.0, 1.2	✓	✓
	3	Center	1.0	✓	✗
	6	Center	1.0	✓	✓
Ethylene	1.5	Top	0.9, 1.0, 1.2	✓	✗
	3	Top	0.9, 1.0, 1.2	✓	✓
	6	Top	0.9, 1.0, 1.2	✓	✓
	6	Center	1.0	✓	✓

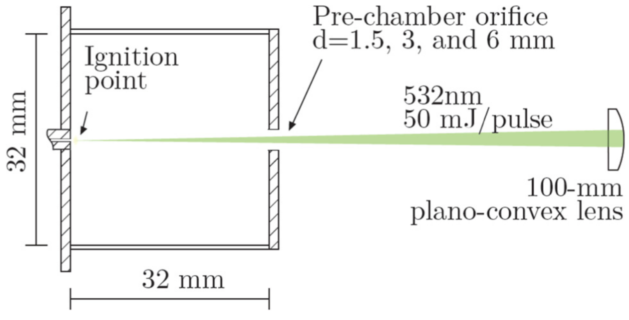

Fig. 1. Pre-chamber jet igniter schematic and ignition method.

High speed chemiluminescence imaging of the OH^* and CH^* radicals were performed independently at 8 kHz with a Photron SA.1 and LaVision HS-IRO high speed intensifier. The imaging system was operated with an exposure time of 120 μs and an intensifier gain of 60. The imaging region captured both the optically accessible pre-chamber and the exiting jet into the ambient. Due to the large difference in signal contrast between the pre-chamber and jet chemiluminescence, an OD 0.2 neutral density filter was used to mitigate chemiluminescence signal from the chamber. The imaging field-of-view was 75 mm wide by 120 mm tall with a resolution of 115 μm/pixel. Table 1 lists whether, for the given sensitivity of the imaging system, if OH^* or CH^* were seen in the jet. A typical turbulent jet structure may include a combination of flame and hot products emerging into fresh mixture which has been ejected ahead of the growing flame kernel. OH^* signal is being used to track heat release and the presence of products, whereas CH^* marks flame reaction zone [14]. The absence of CH^*, in particular, from the jet suggests quenching of reactive layers in the orifice. In this paper, a few of these results are shown in the form of extracted stills and quantitatively analyzed for correlations between the chamber kinematics and jet evolution, with the aim to reveal the location and shape of the reaction zone at various stages of the flame development.

The openFOAM package (version 2.3) has been used for modelling the methane flames. Cases with different diameter of the orifice and different location of the ignition have been considered in this work. The sub-grid scale stress tensor was modelled with the constant Smagorinsky model. The combustion model proposed by Weller et al. [15] was used. This model is based on the solution of the filtered regress variable together with a transport equation for the sub-grid flame wrinkling. Although the premixed flame model used here may not fully account for flame quenching due to heat loss or high stretch, and hence may not reveal fully the details of the flow and flame at the nozzle, the simulations provide some basic flow patterns during the flame expansion process. Furthermore, some useful indications regarding the global behavior of the pre-chamber (e.g. the time evolution of the pressure) for