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Lewis number and Markstein length effects on turbulent expanding flames in a spherical vessel

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ABSTRACT

The turbulent combustion of three different lean fuel–air mixtures has been investigated in a spherical vessel running at different turbulent intensities. Those mixtures were selected to present almost the same unstretched laminar flame speed but various Markstein lengths and Lewis numbers which are relevant parameters to describe flame-stretch interactions. Mie-scattering tomography has been used to measure a global flame stretch and an equivalent flame propagation speed. Results prove that mixtures have same ranking in terms of flame stretch sensitivity as in laminar regime and show the importance of taking into account this parameter in modeling and to evaluate fuel performance in terms of burning speed in Spark-Ignition engine. Flame wrinkling and curvature measurement were also carried out and the wrinkling effect on the flame propagation has been identified.

1. Introduction

Due to environmental considerations, vehicle manufacturers as well as fuel producers are working to reduce CO_2 emissions and improve fuel economy. This results in the emergence of new types of liquid and gaseous fuels for SI engines as for example the ethanol–gasoline blend. However, the use of different fuels modifies the heat release rate, which is piloted by the turbulent burning speed, i.e. the speed of displacement of the unwrinkled flame area. As it is well known, the turbulent burning speed is strongly affected by physico-chemical parameters such as laminar burning speed and Lewis number but also by the local stretch rate. In fact, flame stretch has two main contributions: strain rate and curvature effects [1]. Until recently, measurements of laminar flame speed and stretch rate at relevant conditions for SI engines, i.e. at high pressure and temperature, are sparse. Recent studies provide information about the effects of pressure and temperature on flame speed and stretch sensitivity [2–5].

Nevertheless only a few studies can be found about the impact of flame stretch in SI engines. Concerning turbulent combustion, flame stretch appears to be influenced by the turbulent intensity [6,7] and decreases as a function of time to affect the flame kernel development. Fast-developing flames are associated with lower stretch rate levels than the slow-developing flames [8]. Besides, different flame stretch levels were observed depending on the fuel [9]. In addition, recent work showed different flame growth developments using different fuels [10]. Hence the understanding of flame-stretch interactions inside SI engines remains a great challenge to anticipate the difference of fuel behaviors. Stretch effect on flame propagation in SI Engine is of major importance to deal with the diversity of future potential fuels. Moreover, the better understanding of flame stretch will help to improve CFD engine simulations, which still encounter difficulties in taking this phenomenon into account [11,12]. In a previous study [13], the impact of the engine speed on the stretch rate levels and the dependence of different mixtures to those stretch levels have been studied. It has been shown that the flame stretch sensitivities observed in the laminar regime directly impact the combustion process inside the engine. However the impact of the flame wrinkling on the flame propagation depending on the fuel type or more precisely depending on the flame stretch sensitivity was not fully characterized [14].

The aim of the present paper is then to investigate the impact of the Lewis number and the Markstein length on the flame development and wrinkling in turbulent combustion using Mie-scattering tomography in a spherical vessel and therefore conclude on the impact of those properties in Spark-Ignition Engine.

2. Experimental set-up

Experiments were carried out in a spherical high pressure and high temperature combustion vessel which can be used both for laminar and turbulent flame propagation investigations. A detailed

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Nomenclature

A	flame surface area (m^2)	$S_b{}^0$	unstretched laminar flame speed (m/s)
h	flame curvature (m)	S_{Rs}	turbulent propagation flame speed (m/s)
K_{global}	global flame stretch (1/s)	u'	turbulent intensity (m/s)
L_b	Markstein length (m)	W	flame wrinkling ratio (–)
P	flame perimeter (m)	δ_T	turbulent flame thickness (m)
R_s	flame radius equivalent to the flame area (m)		
R_p	flame radius equivalent to the flame perimeter (m)		

description of the reactive mixture introduction and its ignition can be found in previous works [15]. This combustion chamber is equipped with 6 four-blade fans as shown in Fig. 1. It is a spherical stainless steel vessel with a inner diameter of 200 mm and four quartz windows of 70 mm providing optical access for the implementation of laser diagnostic techniques. The turbulence is generated by the fans (diameter 40 mm, pitch 35.6 mm) located close to the wall inside the combustion chamber and positioned in a regular hexahedral configuration as shown in Fig. 1. The gap between two opposing fans was fixed at 132 mm. The device enables to produce a nearly homogeneous and isotropic turbulence as described by Galmiche et al. in [16]. Three fan speeds were investigated in this study 5000, 6000 and 7000 rpm corresponding to turbulence velocity fluctuations of 0.86, 1.04 and, 1.21 m s^{-1}. The fans directed the flow toward the center of the chamber. Many more information about the turbulence characterization of the device can be found in [16].

Initial pressure and temperature were fixed at 1 bar and 400 K. Three different fuels in lean mixture conditions were investigated in this study. The studied mixtures are the same as [14] and their properties are listed in Table 1.

The objective of this work is to study different mixtures with very similar unstretched laminar flame speed but with different flame stretch sensitivity (Lewis number, Markstein Length) in order to focus on flame stretch and wrinkling effect in turbulent conditions. Mie-scattering laser tomography was used as optical technique. This enables to get precision on the flame front wrinkling. A Dual-Hawk HP Nd:YAG laser was used to illuminate silicon oil droplets. The thin laser sheet was created in the XOY plan (Fig. 1) combining a 300 mm spherical lens and a 25 mm plano-convex cylindrical lens. Flame images were recorded thanks to a Phantom V1610 high-speed camera perpendicular to the laser sheet. The frame resolution was 768 × 768 $pixels^2$ with an acquisition rate of 8000 frames per second synchronized with the laser. The spatial resolution was equal to 101.8 μm/pixel. By post-processing the tomographic images, flame contours can be determined. First subtraction of the background was applied to remove noise. Images were then filtered to correct the non uniformity of the laser sheet and flame contours were obtained after thresholding and binarization. The flame front is then defined as

Table 1
Mixture properties at 1 bar, 400 K.

Fuel	Methane	Propane	Isooctane
Equivalence ratio	0.85	0.72	0.8
Lewis number	0.99	1.88	3.05
Adiabatic flame temperature (K)	2132	1996	2141
Lower Heating Value (MJ. kg^{-1})	50.01	45.75	44.31

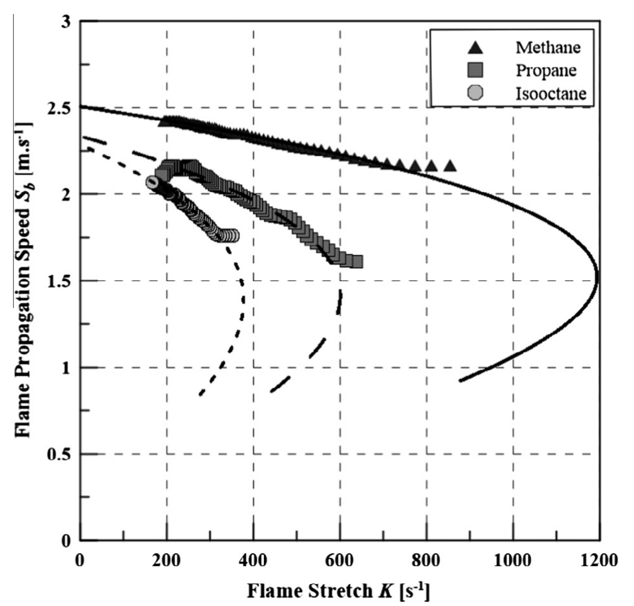

Fig. 2. Laminar flame speed versus flame stretch at 1 bar, 400 K.

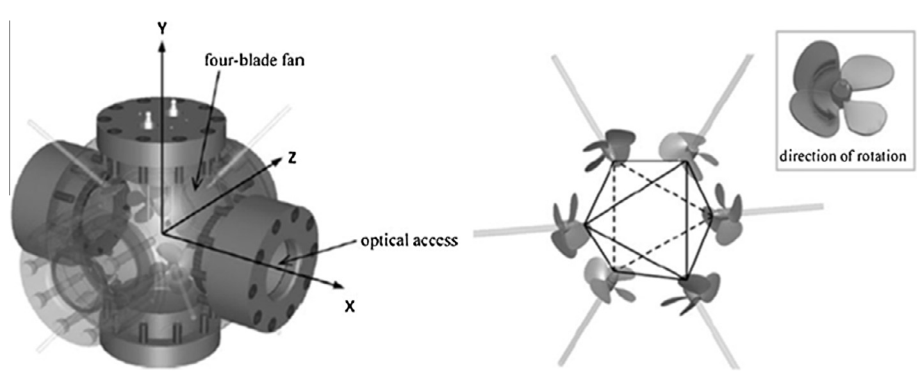

Fig. 1. Turbulent combustion vessel.