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Assessment of elliptic flame front propagation characteristics of iso-octane, gasoline, M85 and E85 in an optical engine

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ABSTRACT

Premixed fuel–air flame propagation is investigated in a single-cylinder, spark-ignited, four-stroke optical test engine using high-speed imaging. Circles and ellipses are fitted onto image projections of visible light emitted by the flames. The images are subsequently analysed to statistically evaluate: flame area; flame speed; centroid; perimeter; and various flame-shape descriptors. Results are presented for gasoline, isooctane, E85 and M85. The experiments were conducted at stoichiometric conditions for each fuel, at two engine speeds of 1200 rpm (rpm) and 1500 rpm, which are at 40% and 50% of rated engine speed. Furthermore, different fuel and speed sets were investigated under two compression ratios (CR: 5.00 and 8.14). Statistical tools were used to analyse the large number of data obtained, and it was found that flame speed distribution showed agreement with the normal distribution. Comparison of results assuming spherical and non-isotropic propagation of flames indicate non-isotropic flame propagation should be considered for the description of in-cylinder processes with higher accuracy. The high temporal resolution of the sequence of images allowed observation of the spark-ignition delay process. The results indicate that gasoline and isooctane have somewhat similar flame propagation behaviour. Additional differences between these fuels and E85 and M85 were also recorded and identified.

1. Introduction

The current issues with our hydrocarbon based economy and its effects on climate change and human life are well documented (for instance [1]). These environmental and socio-political issues are among the most motivating research drivers, providing impetus for research in renewable energy and design-to-specification fuels [2–5]. Nevertheless, developed as well as developing countries still rely to a great extent on conventional fuels powering conventional engines. There is still a lot of room for considerable improvement in understanding the chemical reaction and flame-propagation processes, and reducing the emissions of these engine-fuel combinations. One of the most important ways to analyse combustion processes in engines is to employ 3D-CFD codes, with incorporation of various well refined fuel oxidation and flame propagation mechanisms [6,7]. The models and codes need validation with experimental work accurately describing the exact nature of these in-cylinder processes.

1.1. Flame structure and propagation

Although, flame is defined as the luminous part of the burning gases caused by highly exothermic, rapid oxidation [8]. For simplicity in this study, the earliest and relatively short plasma state of the glowing charge was also considered as a flame. For both moving and standing flames, the flame front is the indicator of where gases heat up and start emitting light [9,10]. This front is considered to consist of two regions: preheat and reaction zones. For instance, Fig. 1 illustrates the top view of the reaction and preheat zones in the chamber of the optical-access engine used in this paper.

The combustion process in SI engines can be divided into four main stages: spark and flame initiation; initial flame kernel development; turbulent flame propagation; and flame termination [11]. The first two stages are of high importance in terms of in-cylinder pressure development [12–16]. These four stages are influenced by: spark energy and duration [17]; spark plug design and orientation [18]; in-cylinder flow field [19]; cyclic cylinder charging [20]; in-cylinder composition [21]; and other related factors. A detailed literature survey on the effects of these parameters on the four stages of combustion appeared in [12].

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Nomenclature

Latin

A	area
B	arbitary region
c_V	isochoric specific heat capacity
d	infinitesimal difference operator
da	semi axial length
D_F	Feret's diameter
f	arbitary function
h	heating value
LHV	lower heating value
m	mass
M	moment of a two dimensional region
O	parameter
p	pressure
Q_{ht}	heat transfer to walls
r	radius
RNS	roundness
$\bar{S}$	average flame speed
SA	semi axes of an ellipse
Sf	shape factor
S_n	flame speed
T	temperature
t	time
U	central moment
u_n	turbulent burning velocity
V	volume
v_g	gas expansion velocity
$\bar{x}$	centroid
$\bar{y}$	centroid

Greek

Δ	finite difference operator
ϵ	axis orientation angle
η_{Vol}	volumetric Efficiency
ρ	density
$\sum$	summation operator

Subscripts

0	spark origin
1, 2	integer
b	fraction burned
i	integer
maj	major
min	minor
p, w	integer
x, y, z	Cartesian coordinates, axes

Acronyms and abbreviations

BTDC	before top dead centre
CA	cranck angle
CMOS	complementary metal-oxide semiconductor
CFD	computational fluid dynamics
CH	clearance height
COV	coefficient of variance
CR	compression ratio
D	dimension
EoI	end of imaging period
EQR	equivalent radius
EVC	exhaust valve closes
EVO	exhaust valve opens
HC	hydrocarbon
IMEP	indicated mean effective pressure
IVC	intake valve closes
IVO	intake valve opens
rpm	revolutions per minute
RSE	relative standard error
SAFS	spherical assumption flame speed
TAI	time after ignition
TDC	top dead centre
ToI	time of ignition

The flame speed S_n (which can be measured from images of the spatial–temporal development of the flame) is given by [9,22]:

$$S_n = v_g + u_n \tag{1}$$

where v_g is the gas expansion velocity immediately adjacent to the flame front and u_n is the stretched laminar burning velocity of combusting air fuel mixture [23]. The turbulent burning velocity equals the laminar velocity with the added effect of the flow field, geometry; wrinkling of the flame front; pressure effects on flame thickness; history of the flame [24]. The effect of the turbulent flow field is crucial for the first and second stage of combustion. It has been shown that the smallest flame kernels are distorted shortly after ignition [25]. The laminar velocity is an intrinsic property of a combustible fuel, air and burned gas mixture. That is defined as the velocity, relative to and normal to the flame front, with which unburned gas moves into the front and is transformed to products [26].

Turbulent burning velocity plays a prime role and directly effects the in-cylinder pressure development, i.e., engine performance. Turbulent burning velocity and laminar burning velocity are important physical properties of fuel air mixtures. It is essential that both of these velocities are derived experimentally from flame speed and in-cylinder pressure measurements [9,14,11,22]. The work produced by an engine is related to the flame speed as can be inferred from the following. The burned mass of charge is given by

$$m_b(t) = (\bar{S}_x\bar{S}_y\bar{S}_z)(t)\rho_b(t)Sf(t), \tag{2}$$

where $\bar{S}_x, \bar{S}_y, \bar{S}_z$ are the average flame speeds in the x, y, z directions. These can be determined by dividing the flame radius along an axis by the elapsed time from ignition. Sf is a shape specific function. The burning of fuel releases energy to the working fluid in the cylinder, given by [26,4]:

$$m_bLHV - (mc_V\mathrm{d}T) - \Sigma h_i dm_i - \mathrm{d}Q_{ht} = p\mathrm{d}V \tag{3}$$

The rate of burning of the air–fuel mixture affects the chemical energy change of the fluid, and this directly affects the indicated work and power output. In Eq. (3) the work done on the piston pdV equals the energy released from the burning fuel m_bLHV, minus the energy required to heat up the charge $mc_V\mathrm{d}T$, minus the heat transfer to walls $\mathrm{d}Q_{ht}$, and adjusted by the masses leaving or entering the chamber $\Sigma h_i\mathrm{d}m_i$. Note: term $\Sigma h_i\mathrm{d}m_i$ can be positive (during fuel injection) or negative (flow to crevice volumes or blow by). Therefore engine performance is highly dependent on flame propagation characteristics within the cylinder.

1.2. Visualisation of initial flame kernel growth in SI engines

In previous engine research images of flames in cylinders showed a significant enflamed volume, but the pressure measurements were not accurate or sensitive enough to indicate the evolving flame kernels [21,15]. Therefore, optical investigation of