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Effects of nozzle geometry on direct injection diesel engine combustion process

R. Payri *, F.J. Salvador, J. Gimeno, J. de la Morena

CMT-Motores Térmicos, Universidad Politécnica de Valencia, Camino de Vera s/n, E-46022 Valencia, Spain

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ABSTRACT

The aim of the current article is to link nozzle geometry, and its influence on spray characteristics, with combustion characteristics in the chamber. For this purpose, three 6-hole sac nozzles, with different orifices degree of conicity, have been used. These nozzles had been geometrically and hydraulically characterized in a previous publication, where also a study of liquid phase penetration and stabilized liquid length in real engine conditions has been done. In the present work, CH and OH chemiluminescence techniques are used to thoroughly examine combustion process. CH-radicals are directly related to pre-reactions, which take place once the fuel has mixed with air and it has evaporated. On the other hand, OH-radicals data provide information about the location of the flame front once the combustion has begun. The analysis of all the results allows linking nozzle geometry, spray behaviour and combustion development. In particular, CH-radicals have shown to appear together with vapor spray, both temporally and in their location, being directly related to nozzle characteristics. Additionally, analysis of ignition delay is done form OH measurements, including some correlations in terms of chamber properties, injection pressure and nozzle diameter.

1. Introduction

Pollutant emission reduction is currently considered to be one of the most important targets of our society. Legislation about pollution coming from vehicles is getting more and more restrictive, so that research is focused to understand physical processes involved in the engine behaviour.

One of the most important subjects in these studies on Diesel engines is the behaviour of fuel once it is injected in the combustion chamber, and its interaction with air. In these terms, it is well known that nozzle geometry and cavitation strongly affect to evaporation and atomization processes of fuel. The study of these phenomena has been the aim of previous studies in the literature [1–8].

Another method to understand what is happening in the engine is analyzing combustion process directly. Several optical techniques have been used by other authors [9–11] to analyze combustion process in the chamber. Soot flame visualization and CH/OH chemiluminescence are the most important techniques referred in literature.

CH-radicals are formed in low temperature reactions. For this reason, they are assumed as an indicator of pre-reactions, which are the first step for the combustion process, once fuel is evaporated [12].

OH- is an intermediate species in high temperature reactions. This implies that OH-radicals are located in the flame front, where vaporized fuel reaches the highest temperatures. Because of this characteristic, OH-appearance is often used to determine ignition delay [12,13].

The aim of the current article is to link nozzle geometry, and its influence on spray characteristics [14–17], with combustion development in the chamber. For this purpose, three 6-hole sac nozzles, with different orifices degree of conicity, have been used. These nozzles had been geometrically and hydraulically characterized in [1], where also a study of stabilized liquid length in real engine conditions has been done. In the present work, CH and OH chemiluminescence techniques are used to thoroughly examine combustion process. The analysis of the results allows linking nozzle geometry, spray behaviour and combustion development.

The paper is structured in four sections. First of all, experimental facilities and methodology are described, paying special attention to image acquisition and processing. A new contour mapping technique, which allows seeing the spatial and temporal evolution of combustion simultaneously, is also introduced. After this, a representation of the experimental results obtained is presented, including a review of some interesting ideas coming from previous studies about stabilized liquid length. In the following section, some analysis about results already presented will be made. In this sense, CH-radicals will be related to liquid length results, while OH provides information about ignition delay, including some correlations for it in terms of chamber conditions and injection parameters. Finally, some general conclusions concerning to chemiluminescence results will be established.

* Corresponding author. Tel.: +34 963879658; fax: +34 963877659.
E-mail address: rpayri@mot.upv.es (R. Payri).

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Nomenclature

A	constant in the ignition delay correlation that represents E_A/R
C_a	contraction coefficient
C_{mv}	fuel mass concentration needed in the spray axis to get complete evaporation
C_v	velocity coefficient
D_{eff}	outlet effective diameter of a nozzle orifice
D_{eq}	equivalent diameter of a nozzle orifice. Defined as $D_{eq} = D_o\sqrt{\frac{\rho_l}{\rho_a}}$
D_i	inlet diameter
D_o	outlet diameter
EA	activation energy
ET	energizing time
K	constant used in the ignition delay correlation
k-factor	nozzle conicity. Defined as $k\text{-}factor = 100 \cdot \frac{D_i - D_o}{L}$
K_p	constant in LL analysis, including the effect of cone angle
L	nozzle length
LL	liquid length
n–m–l	coefficients used in the ignition delay correlation
P_{back}	backpressure
P_{inj}	injection pressure
SOE	start of energizing
SOI	start of injection
t_{mv}	time for a fuel parcel in the axis of a stationary spray to reach a concentration equal to C_{mv}
T	temperature in the engine injection chamber
TDC	Top Dead Center
u_{eff}	effective velocity at the outlet orifice, defined as $u_{eff} = C_a^{1/2} \cdot D_o$
u_{th}	theoretical velocity, obtained from Bernoulli equation as $u_{th} = \sqrt{\frac{2\Delta P}{\rho_l}}$

Greek symbols

ΔP	pressure drop, $\Delta P = P_{inj} - P_{back}$
ρ_a	ambient density
ρ_l	fuel density
λ	wave length
τ	time elapsed from the start of the injection to start of combustion (ignition delay)

2. Experimental methodology

All the experimental tests were done using a standard common rail injection system, including a high pressure pump and a rail, able to regulate pressure inside. Fuel used was Repsol CEC RF-06-99. Main properties of this fuel are reported in Table 1.

2.1. Nozzles

In order to make a study in terms of nozzle geometry influence, three 6-hole sac nozzles have been used. Despite Bosch flow number (defined as mass flow injected in 30 s for an injection pressure of 10 MPa and a backpressure of 0.1 MPa) is the same for the three nozzles, they are made with different degrees of conicity, represented by *k-factor*. Inlet diameter is fixed to approximately 175 μm for all of them. This group of nozzles includes one cylindrical and two convergent geometries. Complete information about their geometry, including inlet and outlet diameters (obtained using the methodology described in [18]), as well as *k-factor*, are shown in Table 2.

2.2. CH and OH chemiluminescence

A single-cylinder two stroke engine is used for combustion visualization studies. The experimental set up is equipped with an optical accessible cylinder head, which contains a cylindrical combustion chamber, as shown in Fig. 1. More information about the engine characteristics can be found in [19].

Table 1
Physical and chemical properties of Repsol CEC RF-06-99 fuel.

Test	Unit	Result	Uncertainty	Methodology
Density at 15 °C	kg/m^3	843	±0.2	EN ISO 12185/96
Viscosity at 40 °C	mm^2/s	2.847	±0.42	EN ISO 3104/99
Volatility				
65% distilled at	°C	294.5	±3.7	EN ISO 3405:01
85% distilled at	°C	329.2	±3.7	
95% distilled at	°C	357.0	±3.7	
Cetane number	–	51.52	±2.5	
Cetane index	–	49.6	±0.51	
Calorific value				
Higher calorific value	MJ/kg		45.58	ASTM D-240/02
Lower calorific value	MJ/kg		42.78	ASTM D-240/02
Fuel molecular composition		$C_{13}H_{28}$		

Table 2
Real orifice nozzle geometry characterization by silicone methodology.

Nozzle	D_i [μm]	D_o [μm]	*k-factor*
1	175	155	2
2	176	160	1.6
3	175	175	0

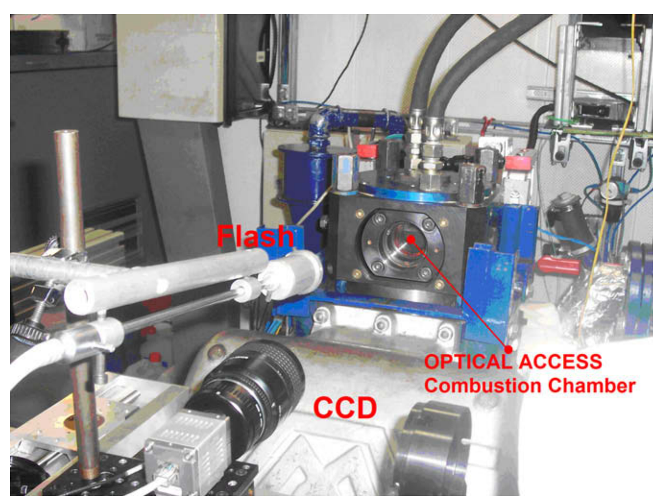

Fig. 1. Experimental facility image.

CH- and OH-radicals can be visualized because they emit light intensity in a well defined wavelength band (λ) of the emitted light spectrum. For this reason, using a proper optical filter, emission corresponding to each species can be discerned from the total amount of light coming from combustion process. In this study, CH is acquired using a filter for λ between 375 and 405 nm, while OH correspond to the range 305–315 nm.

Nevertheless, the total amount of light emitted at these frequencies is small, so an intensified ICCD camera has to be used. In this case, LaVision-Dinamight camera is chosen, giving a resolution of 512 × 512 pixels.