Applied Energy 118 (2014) 100–113

Contents lists available at ScienceDirect

Applied Energy

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

Experimental study of the relationship between injection rate shape and Diesel ignition using a novel piezo-actuated direct-acting injector

Vicente Macian [a], Raul Payri [a,*], Santiago Ruiz [a], Michele Bardi [a], Alejandro H. Plazas [b]

[a] CMT- Motores Térmicos, Universitat Politècnica de València, Spain
[b] GM R&D, Warren, MI, USA

HIGHLIGHTS

- The relationship between injection rate shape and ignition event is studied experimentally at real engine conditions.
- Injection rate shaping affects significantly the premixed phase of the combustion.
- A direct-acting injector prototype is tested in a high temperature/pressure chamber.
- Simultaneous CH^*/OH^* chemiluminescence imaging is performed under a wide range of test conditions.

ARTICLE INFO

Article history:
Received 24 September 2013
Received in revised form 29 November 2013
Accepted 16 December 2013
Available online 8 January 2014

Keywords:
Rate-shaping
Direct-acting
Diesel ignition
Partial needle-lift
Chemiluminescence

ABSTRACT

Injection rate shaping is one of the most attractive alternatives to multiple injection strategies; however, its implementation has been for long time impeded by limitations in the injector technology and therefore, the experimental information available in the literature about this topic is lacking.

In this work, a novel prototype common-rail injector featuring direct control of the nozzle needle by means of a piezo-stack (*direct-acting*) allowed a fully flexible control on the nozzle needle movement and enabled the implementation of alternative injection rate shapes typologies. This state of the art injector, fitted with a 7-hole nozzle, was tested at real engine conditions studying the spatial-temporal evolution of CH^* and OH^* chemiluminescence intensity produced by the fuel combustion. A wide test matrix was performed in an optically accessible hot-spray test rig to understand the influence that partial needle lift and alternative injection rate shapes have on the Diesel ignition

The results showed that alternative injection rate profiles have a substantial impact on the ignition event affecting the premixed phase of the combustion and the location where the ignition takes place. Moreover, the results proved that the modifications in the internal flow caused by the partial needle lift are reflected on the ignition timing: although partial needle lift and injection pressure have similar effects on the mass flow rate, in the first case, the ignition delay is reduced, while in the second, the combustion is delayed as a consequence of a different spray development.

1. Introduction

Fuel-air mixing process, combustion and emission phenomena are necessarily linked together in direct injection Diesel engines [1–5]. In a scenario where the global emission standards require higher engine performances in terms of combustion efficiency and emissions reduction, all the efforts by the engine community to improve the understanding of the fuel atomization, spray development and combustion are largely justified.

Over the past decades, many studies have been carried out to develop a better understanding of the mixing process [6–8] and of the fuel ignition [9–12]. Experimental facilities, such as optically accessible engines [13] and test rig cells [11,14] combined with imaging techniques [5,15], have become the most common tools used in spray research. Throughout the years, the efforts put in place in these studies generated an accurate and deep understanding of the injection combustion event in Diesel engines.

On the other hand, several activities have been performed to advance the flexibility of the fuel injection system, achieving significant improvements [2]. Most of these systems are operated with electro-hydraulic actuation, where the fuel injector is activated using either a solenoid or a piezo-stack; however, the opening of the injector itself is produced by the pressure difference at the two sides of the needle limiting the injection control to an *on-off*

* Corresponding author at: CMT Motores Térmicos, Universitat Politècnica de València, Camino de Vera, Ed 6D, 46022, Valencia, Spain. Tel.: +34 963879658; fax: +34 961826236.
E-mail address: rpayri@mot.upv.es (R. Payri).

0306-2619/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2013.12.025

Notation

Symbol	Description
ASOI	after the start of the injection (μs)
BP	back pressure (MPa)
Ch	voltage level applied to the piezo-stack (*charge*) (–)
CPF	constant pressure Flow (–)
D_0	nominal diameter
ECN	Engine Combustion Network (–)
EGR	exhaust gas recirculation (–)
k-factor	nozzle orifice conicity factor, defined as $k\text{-}factor = 100\frac{D_i - D_0}{L}$ (–)
ICCD	intensified CCD sensor (–)
LOL	lift-off length (mm)
M_{ignition}	fuel mass injected at the moment of second stage ignition (mg)
$O_{2\%}$	oxygen content (vol.) (%)
OH_{peak}	OH^* chemiluminescence intensity peak (see Section 2.6.2) (a.u)
p_{rail}	injection pressure (MPa)
SoCH	first-stage ignition delay (μs)
SoOH	second-stage ignition delay (μs)
SSI	second stage ignition (–)
T_{amb}	ambient temperature (K)
ths_{OH}	intensity threshold for ignition delay (see Section 2.6.2) (–)
λ	parameter defined in Section 4.2 (–)
λ_{foot}	parameter defined in Section 4.2 (–)
ρ_{amb}	ambient density (kg m^{-3})
$\dot{m}$	average mass flow rate (g s^{-1})
$\dot{m}_{f.n.l.}$	average mass flow rate at full needle lift (g s^{-1})
$\dot{m}_{foot}$	average mass flow rate at the first part of a boot shaped injection(g s^{-1})

mode. As a consequence of that, multiple injection strategies are the most employed tool to control the Diesel combustion, although they show strong limitations in minimum dwell-time, and poor atomization during the opening/closing transient [1,3].

The last development of piezo-actuated injectors is the so called *direct-acting* system, where a piezo actuator (stack) is mechanically coupled with the injector needle, having direct control on its position: this technologic achievement enables a fast and precise control of the fuel flow through the injector nozzle [16]. Although many researches have been oriented to the study of the injection event using conventional servo-hydraulic injectors, only a few are discussing the effect of the partial needle lift on injection process [17,20,21] and, to the author knowledge, none of them has been tested at real engine conditions.

In the present work, a prototype multi-hole injector featuring the direct control of the nozzle needle by a piezo-stack, has been used to investigate the effect of partial needle-lift and injection rate shaping on Diesel combustion in a wide range of conditions typical of a real Diesel engine varying rail pressure, ambient temperature and oxygen concentration.

The chemiluminescence signals emitted during the different stages of the combustion have been studied using filtered intensified cameras. In particular, the development of the cool flames has been investigated imaging the emissions of the CH^* radical (filtering at 430 nm) while for the second stage ignition the attention has been focused on the OH^* radical emissions (filtering at 310 nm) [10,13,18]. A novel optical accessible high temperature – high pressure test rig has been employed to mimic the real in-cylinder Diesel-engine thermodynamic conditions [11]. The test rig was modified in order to enable variations in ambient oxygen concentration and to simulate EGR conditions.

The combustion of the 7 spray plumes produced by the multi-hole nozzle have been imaged globally using a large visualization field (~100 mm × 100 mm) centered on the injector nozzle, and the relationship between CH^* and OH^* emissions has been carefully investigated performing a simultaneous image with two synchronized ICCD cameras.

Finally, the images captured have been processed using a purpose-made Matlab routine, developed to present in comprehensive color-maps the data related to each test and to compare the time evolution of the event under different test conditions. Finally, the combustion-related characteristics parameters (e.g. ignition delay and location) have been measured and analyzed.

2. Material and methods

2.1. Injection system

The fuel supplied to the injector is provided by a common rail system constituted by a high pressure pump and a conventional rail with a pressure regulator. The system allows fuel injections at high and relatively constant pressure (up to 200 MPa). All the injection system is electronically controlled by a ECU and all the settings are introduced digitally.

The prototype piezoelectric direct-acting injector is fitted with a 7-hole nozzle: the orifices are equally separated and oriented with 156° opening angle; the orifice outlet diameter is $D_0 = 156$ μm and *k-factor* = 1.5 [19]. All the nominal features of the injector are listed in Table 1. In this study, the injector body temperature is controlled at 343 K [11], and commercial Diesel fuel (EU standard EN590) was used with 812 kg/m^3 density and 1.9 mm^2/s kinematic viscosity (at 343 K).

The injector used in the present work has the piezo-actuator directly coupled with the injector needle and thus, the voltage applied to the piezo-stack (in this work, also called *charge* or *Ch*) controls the needle position: the needle lift increases with the voltage applied. Since it was not possible to measure the actual needle lift, a hydraulic characterization was performed to study the relationship between mass flow rate and the voltage applied [17]. Although an important and highly-repetitive reduction in the mass flow rate is achieved by needle throttling (reducing the voltage or *charge* applied), the relationship between mass flow rate and *charge* is complex since other parameters, like injection pressure and injector temperature, are affecting the injector behavior.

Table 1
Injector features.

Injector features	
Brand	Continental
Nozzle seat type	Micro-sac
Number of orifices	7
Spray included angle	156°
Outlet diameter	0.156 mm
k-Factor[*]	1.5
Discharge coefficient	0.81

[*] *k-Factor* definition is defined in [19].