Applied Energy 106 (2013) 152–162

Contents lists available at SciVerse ScienceDirect

Applied Energy

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

Study liquid length penetration results obtained with a direct acting piezo electric injector

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HIGHLIGHTS

- ▶ A direct acting injector capable of controlling needle lift has been used to determine liquid phase penetration.
- ▶ The influence of injection pressure, chamber density and chamber temperature have been measured.
- ▶ When needle lift is reduced the stabilized liquid length is shortened.
- ▶ The relationship between needle lift and liquid length makes needle lift as a new way to control the injection event.

ARTICLE INFO

Article history:
Received 3 October 2012
Received in revised form 19 December 2012
Accepted 7 January 2013
Available online 21 February 2013

Keywords:
Diesel
Injection
Spray evaporation
Needle control
Liquid length

ABSTRACT

A state of the art prototype common rail injector featuring direct control of the needle by means of a piezo stack (direct acting) has been tested. Liquid phase penetration of the sprays in diesel engine-like conditions has been studied via imaging technique in a novel continuous flow test chamber that allows an accurate control on a wide range of thermodynamic conditions (up to 1000 K and 15 MPa). This state of the art injector fitted with a 7-hole nozzle, allows a fully flexible control on the nozzle needle movement, enabling various fuel injection rate typologies. The temporal evolution of the seven sprays has been studied recording movies of the injection event in evaporative conditions via Mie scattering imaging technique and using a high speed camera. The results showed a strong influence of needle position on the stabilized liquid length while the effect of the injection pressure is negligible: the decrease of the needle lift causes a pressure drop in the needle seat and thus a reduction in the effective pressure upstream of the orifices (in the nozzle sac). According to known literature the stabilized liquid-length depends mainly on effective diameter, spray cone-angle and fuel/air properties and does not depend on fuel velocity at the orifice outlet. Therefore, due to small change in the spray cone-angle, higher injection pressures give slightly lower liquid length. However, partial needle lifts has an opposite effect: when needle is partially lifted a dramatic increase of the spray cone-angle and a consequent reduction of the liquid length are observed. A deeper analysis revealed that low charges are linked also to higher hole to hole dispersion and flow instabilities. Needle vibrations caused by the fuel-needle interactions with fuel flow at partial needle lift and the onset of cavitation in the needle seat are likely the causes of this unexpected behavior. Finally, the effect of injection rate shaping on the transient liquid penetration is presented, showing the capability of the injector to control the liquid length along the injection event. This feature, when applied in a real engine, yields to develop new injection strategies to avoid fuel wall impingement.

1. Introduction

An important part of the study of the combustion process in diesel engines is based on spray flow mechanisms because of the importance that they have on engine performance and pollutant emissions [1–5]. In-cylinder diesel spray development starts with liquid fuel being injected in an ambient with a certain pressure and temperature. Once injected into the cylinder, the spray changes not only geometrically but also temporally approaching the walls, while it interacts with the surrounding air leading to vaporizing process of the fuel and eventually combustion. Focusing on mixing process, fuel atomization has an important influence on spray local composition, which has an effect on spray penetration and structure [6]. For example, low density conditions could cause

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http://dx.doi.org/10.1016/j.apenergy.2013.01.027

Nomenclature

ASOI	after the start of injection	LL_m	average liquid length
BP	back pressure	$\dot{m}$	mass flow rate
C_d	discharge coefficient	P_{rail}	rail fuel pressure
C_a	area coefficient	T_{amb}	ambient temperature
$C_{m.v}$	constant defined in 4	T_f	coolant temperature
C_v	velocity coefficient	q	linear regression constant
Ch	Piezo stack charge level	t	time
D_0	orifice outlet diameter	x_i	time related to the raw datum
ECU	electronic control unit	y_i	raw datum
f.n.l	full needle lift	λ	parameter defined in Section 4
k	linear regression constant	Δt	time window for data averaging
Kp	constant defined in 4	ρ_{amb}	ambient density
LL	liquid phase penetration	ρ_f	fuel density
LL_{th}	theoretical steady liquid length	θ_m	spreading angle

liquid impingement on the walls, which may result in unburned hydrocarbons (UHCs) and carbon monoxide (CO) emissions; the opposite might cause high combustion rates and hence high in-cylinder local temperature and NO_x formation. A compromise between both situations and correct after-treatment techniques are determining factors for current engine performance.

Researchers have performed a lot of studies in order to understand how the mixing process occurs. In such studies the main macroscopic parameters of a spray have been identified as liquid length, vapor penetration, and cone angle [6–11]. Experimental facilities such as optically accessible engines [12] and test rig cells [13–16] have been used for fundamental research of these parameters. Mie-scattering imaging and shadowgraphy are among the most common techniques used to temporally characterize liquid length and vapor penetration, respectively [16]. Throughout the years, basic studies have been made in order to investigate the effects on spray liquid length and vapor phase location induced by engine parameters such as orifice diameter [17], ambient gas conditions [18], injection pressure [19] and fuel characteristics [20,21].

Another important aspect of diesel combustion is the fuel injection system. Over the past decade several fuel injection systems have been used [1,21–23]. All these systems were operated with electro-hydraulic actuation and the injector was activated using either a solenoid or a piezo stack; however, the opening of the injector itself was produced because of a pressure difference at the two sides of the needle.

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, controlling directly its position: this technologic achievement allows a fast and precise control of the fuel flow through the injector nozzle. Although many researchers 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 [25].

The study carried out by Payri et al. in [25] showed the big potential of the direct acting injector in the control of the fuel mass flow rate: in this work they showed how, controlling the needle lift, it is possible to reduce the mass flow rate, obtaining a relationship between needle lift and sac pressure. Adjusting the voltage applied to the piezo-stack, the fuel mass flow rate can be controlled by the electronic control unit (ECU) and injection rate shaping (modulating the mass flow during the injection) is enabled. Both these facts represent a step forward in the capabilities of the injection system and thus in the control of combustion and pollutant emission of a current direct-injection diesel engine. However, the effect of partial needle lift on the spray development and combustion is still not clearly understood: for this reason a full characterization of the injector is required to make the most of it when employed in a real engine.

The first step of this path is an experimental study to capture the liquid phase of the sprays injected by the direct acting injector in evaporative non-reacting conditions. The effect of the partial needle lift has been observed under a wide range of diesel like conditions using a high temperature and high pressure test rig [4]. The facility is capable of reaching 15 MPa ambient pressure and 1000 K ambient temperature; the large optical accesses and the wide test section allow studying the spray with high accuracy in a homogeneous temperature and nearly quiescent environment. In this work, different parameters have been varied: ambient temperature, ambient pressure, injection pressure and needle lift (piezo stack charge).

2. Materials and methods

In this section, the fuel injection system, the high pressure-high temperature test rig and the optical arrangement employed for the tests are described.

2.1. The fuel injection system

The fuel feeding 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) [22,23,26]. All the injection system is electronically controlled by the ECU and all the settings are introduced digitally.

The prototype piezoelectric direct-acting injector is fitted with a 7-hole nozzle with outlet diameter $D_0 = 152\ \mu\text{m}$ and k-factor = 1.5 [3]. All the nominal features of the injector are listed in Table 1.

As mentioned before, the piezo actuator is directly coupled with the injector needle and thus, the needle position can be controlled by applying a different voltage to the piezo stack (or piezo stack charge): the needle lift is higher when the voltage applied increases. Being not possible to measure the real needle lift, the hydraulic characterization described in [25] was performed to study the relationship between mass flow rate and piezo stack charge. Although an important reduction in mass flow rate is achieved by means of needle throttling (reducing the piezo-stack charge applied), a quantitative relationship between mass flow rate and piezo stack charge was not found: other parameters were found to affect piezo-stack behavior such as injection pressure and piezo stack temperature. The mass flow rate and the parameters obtained from hydraulic characterization (discharge coefficient