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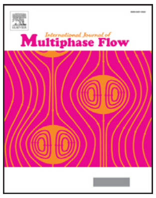

Velocity field analysis of the high density, high pressure diesel spray

Raul Payri [a,*], Juan P. Viera [a], Hua Wang [b], Louis-Marie Malbec [c]

[a] CMT-Motores Térmicos, Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia,Spain
[b] Department of Energy, Politecnico di Milano, Via Lambruschini 4, 20156 Milan, Italy
[c] IFPEN, 1 & 4, avenue de Bois-Préau, 92852 Rueil-Malmaison Cedex, France

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ABSTRACT

In this study, particle image velocimetry (PIV) measurements have been performed extensively on a non-reactive dense diesel spray injected from a single orifice injector, under various injection pressure and steady ambient conditions, in a constant flow chamber. Details of PIV setup for diesel spray measurement without additional seeding are explained first. The measured velocity profiles are compared to those obtained from other similar measurements performed in a different institution, as well as those obtained from a 1D spray model simulation, presenting in both cases a good level of agreement. In addition, the velocity fields under various injection pressures and ambient densities show the dominant effects of these parameters on the behavior of diesel spray. The self-similarity of the transverse cut profiles of axial velocity is evaluated, showing that the measurements are in agreement with the hypothesis of self-similar velocity profiles. Finally, the effect of injection pressure and ambient density on the velocity fluctuations is presented and analyzed as well. While the experimental results presented here could help to understand the complex diesel fuel–air mixing process during injection, they also provide additional spray velocity data for future computational model validation, following the main idea of the Engine Combustion Network.

Introduction

The air–fuel mixing process is one of the key processes governing the combustion and the pollutant formation in diesel engines (Mobasheri et al., 2012; Pickett and Siebers, 2004). Solutions to recent and ever increasing concerns of fuel efficiency and pollutant emissions are, therefore, closely linked to a better understanding of this mixing process. Because of this, the diesel spray development has been extensively studied, and the characteristics of liquid phase (Bardi et al., 2012; Herfatmanesh et al., 2013; Naber and Siebers, 1996; Payri et al., 2012, 2013a) and vapor penetration (Bardi et al., 2012; Herfatmanesh et al., 2013; Pastor et al., 2012; Payri et al., 2013b) are now quite well known. These experiments have enabled the development of very useful 1D spray models (Desantes et al., 2009, 2007; Musculus and Kattke, 2009; Pastor et al., 2008; Pickett et al., 2011)] that allow for fast and reliable predictions that effectively reduce testing times and costs necessary for new developments to comply with efficiency standards, emission regulations, etc.

However, a relatively few studies have focused on velocity fields inside the spray, which are of great importance for model validation (Kolakaluri et al., 2010). Payri et al. (2008) have performed PDPA (phase doppler particle analyzer) on the spray recently; they found that the application of this technique to diesel sprays is challenging and has certain limitations imposed firstly by the high droplet number concentration and secondly by the droplets typical high velocity and small size. Particle Image Velocimetry (PIV) is another laser diagnostics technique which can be utilized to measure instantaneous velocity of complex flow fields. Many authors have employed this technique in fuel sprays with external seeding (Cao et al., 2000; Driscoll et al., 2003; Meijer et al., 2012a; Zhu et al., 2013) but out of these studies, only Cao et al. (2000) and Meijer et al. (2012a) perform measurements of the velocity field inside the high ambient density diesel spray. Moreover, to the authors' knowledge, there are very few authors that have successfully measured spray internal velocity fields without the use of seeding particles (Zama et al., 2012, 2013; Zhu et al., 2012). Out of all these PIV experiments, only Meijer et al. (2012a), Zama et al. (2012, 2013) and Zhu et al. (2012) have performed internal spray velocity measurements for current-trend small nozzle (of outlet diameter $D_o < 200\ \mu m$), high injection pressure and high ambient density conditions.

The main goal of this paper is to analyze the velocity fields inside the non-vaporizing, high ambient density diesel spray, through planar seeding-free PIV analysis. This is relevant not only because non-vaporizing sprays present very similar behaviors to vaporizing sprays for mixing processes (Hiroyasu and Arai, 1990; Naber and Siebers, 1996; Payri et al., 2014; Zhu et al., 2012), but also because

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[*] Corresponding author. Tel.: +34 963 879 658; fax: +34 963 877 659.
E-mail address: rpayri@mot.upv.es (R. Payri).

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performing PIV in vaporizing, high ambient density/injection pressure conditions presents a real challenge regarding the experimental test rig and the correct supply of seeding particles.

Therefore, velocity field measurements were carried out for different test conditions. To further evaluate the measurements, a well-documented nozzle and set of test conditions were selected. The evaluation of the measurements consists of comparing both similar experiments performed at two different institutions (CMT-Motores Térmicos using liquid fuel droplets as tracers and IFP Energies Nouvelles using ceramic nanoparticle seeds) and also comparing experimental results with a well-documented 1D spray model, first introduced by Desantes et al. (2009, 2007), and Pastor et al. (2008). Finally, after the assessment of the seeding-free technique is presented, an analysis of the experimental velocity field at parametric variations of injection pressure and ambient density is held.

Experimental setup and methodology

The fuel injection system

A common-rail injection system was employed during the experiments, which allows injection pressure up to 2000 bar (Payri et al., 2012, 2013a, 2013b). The fuel utilized was n-dodecane, injected through a single orifice nozzle (ECN nozzle 210675, BOSCH solenoid actuated injector) (Kastengren et al., 2012), with an outlet diameter $D_o = 89.4\ \mu$m and a k-factor = 1.5. The injector tip temperature was controlled using a customized injector holder, which guarantees the uniform temperature through the whole injector body. The nozzle is also isolated from the chamber temperature with a ceramic shield liner which features a small axial orifice to allow the free pass of the fuel spray.

The high pressure and high temperature test rig

The tests have been performed in a high temperature, high pressure, constant flow test chamber where the in-cylinder thermodynamic conditions of a diesel engine at the time of injection can be reproduced. The test chamber allows a maximum ambient temperature of 1000 K and maximum pressure of 150 bar. The test section has three large windows (128 mm in diameter) placed orthogonally in order to have complete optical access to the injection-atomization process. The complete test rig functioning and principles are precisely described in previous works presented by Payri et al. (2013a, 2013b, 2015). In this study, the vessel was filled with nitrogen to guarantee the non-reacting conditions sought.

Since the injector tip is directly exposed to the chamber gas, the actual injector tip temperature depends on the chamber gas temperature, chamber gas density, and injector coolant temperature (Payri et al., 2012). Thus, injector coolant temperature was adjusted according to the chamber conditions to guarantee the ECN injector tip temperature requirement of 363 K.

Experimental test matrix

The experimental test matrix, presented in Table 1, focuses on studying the velocity field of a steady, fully developed spray at different test conditions. The injector utilized, the ambient densities and injection pressures selected are those of interest to the Engine Combustion Network (ECN) (Bardi et al., 2012; Kastengren et al., 2012; Meijer et al., 2012b). The ECN is a worldwide group of institutions that perform experiments and computational fluid dynamics, whose aim is to advance the state of spray and combustion knowledge at engine-relevant conditions. This initiative has permitted the construction of a large, public set of experimental data based on a particular point of working conditions: the so called “Spray A” condition is a low-temperature combustion condition relevant to engines that use moderate EGR. The main target of this experimental dataset is to enhance model validation capabilities and overall knowledge and understanding of the diesel sprays.

Table 1
Experimental test matrix.

Target parameter	Values	Units
Fuel	n-dodecane	–
Nozzle reference	210675	–
Outlet diameter	89.4	μm
Nominal k-factor	1.5	–
Ambient temperature	500	K
Ambient density	22.8–15.2–7.6	kg/m^3
Ambient pressure	33.2–21.9–11.0	bar
Injection pressure	500–1000–1500	bar
Reynolds number	3.18e4–4.58e4–5.65e4	–
Weber number	3.23e5–6.89e5–10.32e5	–
Ohnesorge number	1.8e−3–1.8e−3–1.8e−3	–
Injector coolant temperature	343	K
Oxygen concentration	0	%

In this case, the study seeks to enhance the ECN database by providing velocity fields and turbulent statistical behavior for the Spray A test conditions and parametric variations around these. Compared to the standard ECN Spray A conditions, a lower ambient temperature condition (500 K) was selected to achieve the adequate droplet density for PIV measurements – since the fuel droplets are the actual tracers for the velocity measurements. Higher ambient temperatures would cause evaporation of most of the fuel droplets and thus leave few droplets left to trace. Since ambient temperature was kept at 500 K, ambient pressures were adjusted accordingly to obtain the target ambient densities inside the chamber (see Table 1). Note that the dimensionless numbers presented in Table 1 are calculated at the orifice outlet, with the hydraulic performance data available for this nozzle from the ECN experimental campaigns (Kastengren et al., 2012).

The flow field of the steady, fully developed liquid spray is the main concern of this study. Therefore, the laser timing with respect to the injector trigger signal (Start of Energizing, SOE) was set so that images were acquired late enough to guarantee a steady, fully developed spray, but the tip of the spray remained inside the frame so as to allow for velocity measurements in the spray tip region. This means that the actual frame timing with respect to the SOE is not constant through the test matrix, but adjusted to find the above criteria for each test condition.

Optical setup

The optical setup utilized for these experiments (shown in Fig. 1) consisted in a two-dimensional PIV setup, constituted by a double-pulse Nd:YAG laser, two laser mirrors, sheet optics and a double pulse camera. The camera, situated perpendicular to the laser sheet plane, captured light scattered by the liquid droplets in the spray. The laser was introduced from the front of the spray tip, towards the nozzle. Although frontal illumination produces an unbalanced intensity distribution along the macroscopic spray (a strong light attenuation was found near the injector tip), it has been proved to have a negligible effect on an analysis such as a PIV (Dankers et al., 2008), which was observed in this study as well. Table 2 summarizes the rest of the optical setup components and characteristics:

The time step between frames is also another important variable in a proper setup PIV system. If set too short, the very small particle movements detected become comparable to pixel wise spatial resolution, and actual velocity measurements are then left to sub-pixel interpolations which can introduce additional problems in small particles, where peak locking may occur (Cholemari, 2007; Overmars et al., 2010). A certain amount of particle movement (thus, a long