

Spray Visualization and Characterization of a Dual-Fuel Injector using Diesel and Gasoline

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ABSTRACT

This paper focuses on the spray and atomization characteristics of a Dual-Fuel Injector (DFI) which includes a primary and a secondary fuel inlet. Three injectors were analyzed in this study. Apart from the DFI, two conventional diesel injectors were tested as baselines for comparison - a piezo-electric and a solenoid injector. The rail pressures ranged from 200 - 500 bar for the conventional injectors. The DFI was tested first as a single-fuel injector (by sealing the secondary inlet) at pressures ranging from 100 - 300 bar, and then in its dual-fuel mode with the primary inlet pressure ranging from 100 - 300 bar, and the secondary inlet at 25 bar higher than the primary pressure. Injection duration of 0.5 ms was chosen for the experiment. High-speed Mie scattering images were recorded to capture the spray evolution. Phase Doppler Anemometry (PDA) measurements were conducted at different locations in the spray for the acquisition of droplet sizes and velocity distributions. The high-speed images showed that the conventional injectors produced a spray with a wider spray cone angle, relative to the DFI injector which had a narrower spray cone angle leading to equal radial and axial spray penetration, and displaying a fine mist of gasoline droplets surrounding the diesel fuel jets. The DFI injector's spray provided superior atomization compared to the conventional injectors. The drop size of the dual-fuel spray was slightly higher than the single-fuel spray due to collision and coalescence of the diesel droplets with the fine gasoline droplets.

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INTRODUCTION

Today, as energy resources are drying up and environmental pollution is becoming more and more severe, alternative fuel development and new combustion concepts for cleaner and more efficient internal combustion engine operation have become increasingly important [1]. Direct fuel injection technology, applicable to both SI and CI type of engines, has received much attention in recent years due to its high energy conversion efficiency. Fuel injections, and the subsequent fuel/air mixing process, play an important role in the engine performance. Superior fuel atomization, producing fine droplets, will enhance the air/fuel mixing rate and reduce the emissions from combustion whereas poor atomization could result in incomplete fuel vaporization and spray impingement on the cylinder walls, which cause high levels of hydrocarbon and carbon monoxide emissions as well as fuel/oil dilution, and consequently deteriorated engine performance.

Many combustion strategies have been investigated to meet the future requirements of clean, efficient diesel engines. Most of the current strategies fall into the category of low temperature combustion (LTC). LTC is desired because low combustion temperatures result in NO_x reductions, due to the high activation energy of NO formation reactions [2]. In addition, low temperature combustion strategies typically utilize injection timings that allow for increased air/fuel mixing prior to the start of combustion; thus, rich regions are reduced and soot formation is inhibited. Many researchers have shown that LTC strategies such as Homogeneous Charge Compression Ignition (HCCI) and Premixed Charge Compression Ignition (PCCI) are promising techniques for simultaneous NO_x and soot reduction [3, 4, 5, 6, 7, 8]. Due to the existing fuel infrastructure, most HCCI and PCCI research has been conducted using either gasoline or diesel fuel. However, in their neat forms, each fuel has specific advantages and shortcomings for LTC. For instance, gasoline has a high volatility; thus, evaporation is rapid and a premixed charge can

be obtained using port fuel injection. However, because gasoline resists auto-ignition, it becomes difficult to achieve combustion at low-load conditions [9, 10]. Conversely, diesel fuel has superior auto-ignition qualities; however, this can result in difficulty controlling the combustion phasing as engine load is increased. To find the optimum fuel for HCCI over a wide engine speed/load range, experiments were performed by Bessonette et al. [11]. They suggested that the best fuel for HCCI operation may have auto-ignition qualities between those of diesel fuel and gasoline, depending on the engine speed and load. Based on these results and experiments by Inagaki et al. [12], the RCCI strategy was developed to allow the fuel reactivity to be optimized at all speeds and loads, providing an increased engine operating range for premixed LTC [13, 14, 15, 16]. In the newer combustion concepts such as HCCI and PCCI where the pilot/main injection is much advanced, the impact of the charge mixture preparation is emphasized since it has been reported that excessive mixture stratification can lead to non-negligible presence of overly rich ($\phi > 1.3$) or overly lean ($\phi < 0.4$) equivalence ratio zones, which undergo incomplete oxidation under highly dilute, low-temperature combustion conditions, causing significant amounts of unburned hydrocarbons (UHC) and carbon monoxide (CO) emissions [17, 18]. In this regard, the air/fuel mixing is pivotal for both conventional and advanced combustion technologies.

The injection-associated parameters such as the injection pressure, injector orifice characteristics, spray cone angle, spray penetration length etc. have been intensively studied and analyzed for characterizing sprays using various laser diagnostic techniques and for pursuing optimal atomization characteristics [19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29]; different injector/atomizer configurations and designs have also been proposed and investigated for the purpose of achieving better air/fuel mixing by increasing either the swirl flow or plume-to-plume interaction [30, 31].

Due to lacking a practical dual-fuel injector for direct injection applications, on-demand separately direct injection of both gasoline/ethanol and diesel fuel without pre-blending is rare in literature. However, direct injection is considered as most promising. A single injector with dual fuel injection can eliminate the need for two set of fuel injectors dedicated for each fuel, thus improve simplicity and reduce the cost of the dual fuel engine platform. Dual fuel direct injection can also eliminate the difficulty of cold starting, and issues related to port injection and fuel blending.

EXPERIMENTAL SETUP AND METHODOLOGY

Experimental Setup

The experiment was carried out on an optical engine facility, where only the fuel injection system is used as shown schematically in Fig. 1 (a). For the diesel fuel circuit, a Bosch CP1 high pressure pump (1350 bar max.) coupled with electric motor was responsible for delivering the fuel into the common

rail. Pressure is varied using a pressure regulator which is controlled by a LabView interface. The control is made possible through a custom-designed circuit which supplies the necessary voltage to the pressure regulator in order to vary the fuel pressure. For the gasoline fuel circuit, the fuel was supplied by a non-return loop comprised of a fuel canister pressurized with nitrogen gas. The can was made from 1 1/2" schedule 40 stainless steel pipe and capped on both ends with pipe fittings. The nitrogen inlet was on the top and the fuel outlet was on the bottom. The fuel pressure was set with a Tescom high-pressure regulator connected to the can with a braided stainless steel hose. A check valve prevented any liquid fuel from entering the nitrogen supply line. Stainless steel 1/4" tubing was used for the fuel line and compression fittings were used to assemble the system. A bleed valve at the top of the fueling system was used to expel vapor from the system. After the bleed valve, another braided stainless steel hose supplied fuel to the injector. A diagram of the system is shown in Figure 1 (b). Some important properties of the two fuels, relevant to atomization and vaporization are listed in Table 1.

The injection system is controlled by a locally-made injector driver, which provides the required current to lift the needle inside the injector at a given timing. The returned fuel from both the injector and the high pressure pump are cooled through an air-cooled heat exchanger before being recollected in the fuel tank so that the injection system would not be overheated. The injection duration and frequency of injections are controlled using a Digital Pulse Generator, and a Function Generator, both of which work in conjunction with the LabView interface.

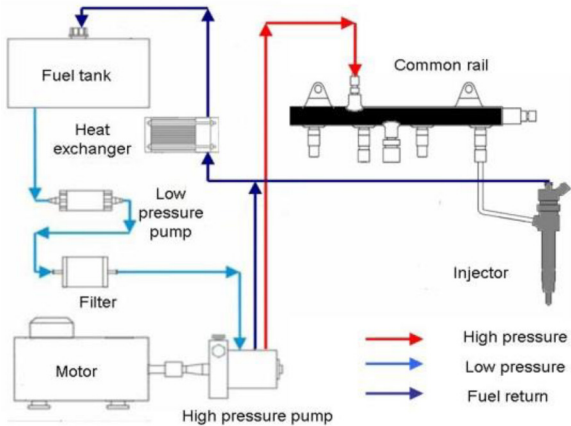
The front view and top view of the dual-fuel injector (DFI) is shown in Fig. 2. It has two inlets - a primary inlet at the rear end of the injector and a secondary inlet towards the middle of the injector body. In this study, no. 2 diesel was supplied through the primary inlet and pure gasoline was supplied to the secondary inlet.

Table 1. Properties of Fuels tested

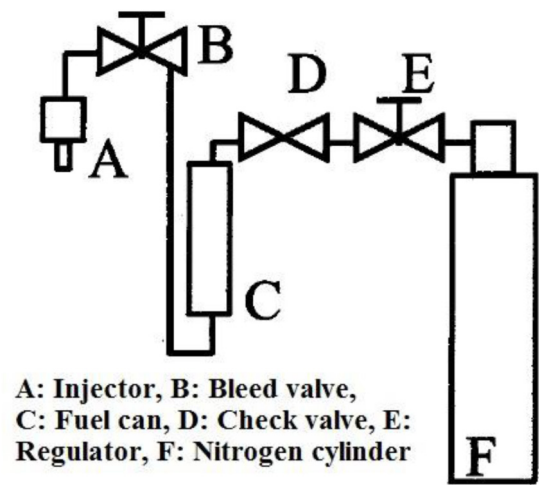
Property	Gasoline	No. 2 Diesel
Chemical Formula	C4 to C12	C3 to C25
Molecular Weight	100–105	≈200
Specific gravity, 60° F/60° F	0.72–0.78	0.81–0.89
Density, lb/gal @ 60° F	6.0–6.5	6.7–7.4
Viscosity (cSt @ 68°F)	0.5	~3-7
Boiling temperature, °F	80–437	370–650
Reid vapor pressure, psi	8–15	0.2

Table 2. Experimental conditions

Injector	Primary Inlet Pressure (bar)	Secondary Inlet Pressure (bar)
Conventional Injector 1 (Piezo-electric)	300, 400, 500	NA
Conventional injector 2 (Solenoid)	300, 400, 500	NA
Dual-Fuel Injector	100, 200, 300	125, 225, 325



(a)



(b)

Figure 1. Experimental Setup - Fuel Injection System - (a) No. 2 Diesel
(b) Gasoline



Figure 2. Front view and top view of dual-fuel injector

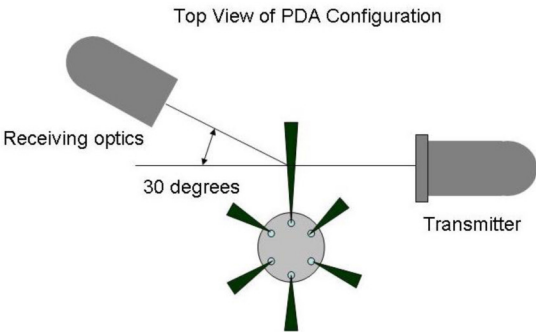
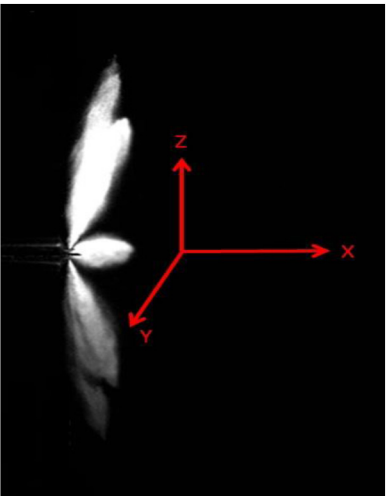
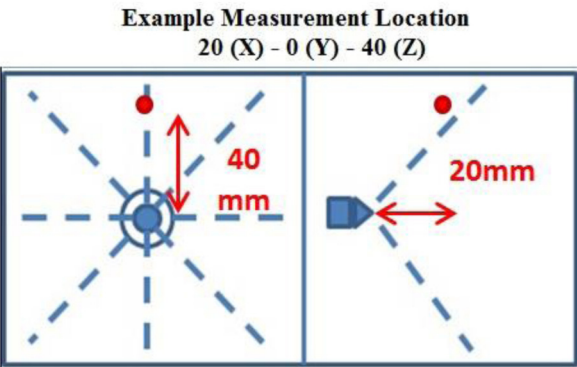


Figure 3. PDA configuration



(a)



(b)

Figure 4. (a) PDA Co-ordinate System (x, y, z) (b) Example location (20-0-40)

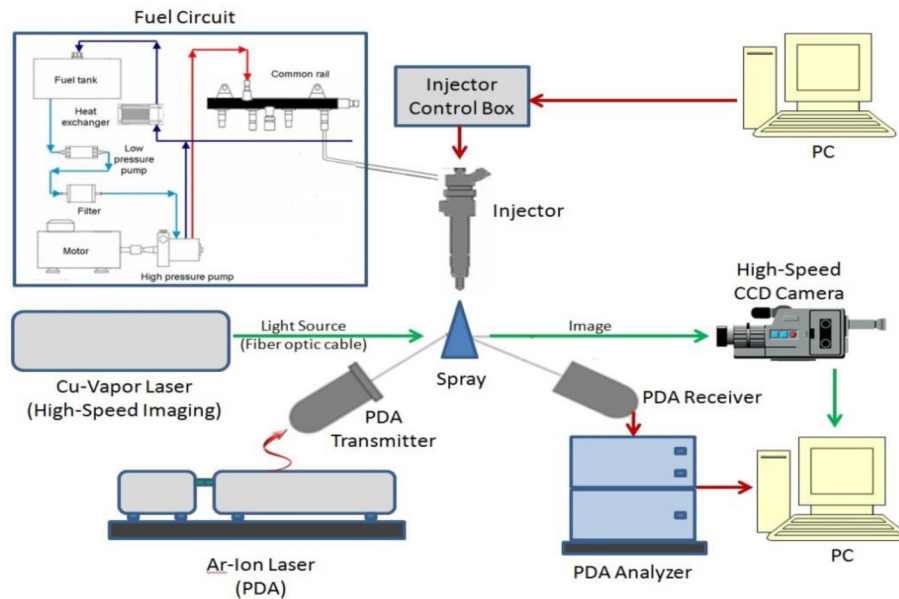


Figure 5. Experimental Setup - Optics & Laser Diagnostics

Laser Diagnostics

Back light illumination was used for capturing the time resolved injection event. A phantom V7 high speed camera was used at a speed of 15037 fps, corresponding to a time resolution of 67 μ s. An Oxford copper vapor laser (Model: LS20-50), synchronized with the camera, was used as the backlight source. The injector was positioned such that the spray direction was perpendicular to the light source/camera to obtain the side view images, and the injector was tilted by 90 degrees to make the spray parallel to the light source/camera to obtain the bottom view images. The laser light was delivered through a fiber and projected onto a white paint coated glass to form a homogeneous background. The camera was triggered by the injection signal and the exposure time was set to 3 μ s. For each case, a minimum of three injections were conducted for any quantitative analysis.

A 2D Dantec PDA system with a BSA P60 processor coupled with a 58N70 detector unit was used for the measurement of the droplet velocities and diameters. The transmitting and receiving optics were installed on a three dimensional traverse so that the measuring position can be precisely controlled. An argon-ion laser with a maximum power of 8.5 W was used and the output was aligned with the fiber optic unit. This unit was responsible for splitting the laser beam into two pairs of different wavelengths; each pair delivering two beams with equal intensity after proper alignment with the manipulators. The first pair consisted of green beams with a wavelength of 514.5 nm, responsible for the axial velocity component, while the second pair consisted of blue beams with a wavelength of 488 nm, responsible for the radial velocity component. A Bragg cell unit is positioned inside this fiber optical unit to provide a 40 MHz frequency shift between two the beams within each pair. Light scattered by the droplets was collected by a 310 mm

focal length lens positioned at 30 degrees to the plane of the two incident green beams to ensure that refraction dominated the scattered light as can be seen in [Figure 3](#).

The signal from the photomultipliers was transmitted to the processor unit where all the data processing was carried out. The processor was connected to a desktop computer via an Ethernet adapter where all the acquired data was saved for further analysis. The measurements, similar to the high speed images, were synchronized with the injection signal, and a time window of 10 ms after SOI was used as the limit for each injection event.

A proper configuration of parameters such as signal to noise ratio (SNR), signal gain, record length, applied photomultiplier voltage was chosen according to different testing cases to ensure a reasonably good data rate (above 200 samples/second) and validation rate (above 80%). Difficulties in measurements were encountered for high pressure injection, especially in the central part of the spray jet and near the nozzle exit region owing to the strong attenuation of the incident laser beams and the scattered light. The PDA experimental setup is shown in [Figure 3](#). The direction of the axes is shown in [Figure 4](#). The entire fuel injection and laser diagnostic setup (High-speed imaging as well as the PDA) is shown in [Figure 5](#). There are several validation criteria for the LDA and PDA. First, there is the burst detector which is triggered by a signal that exceeds a certain threshold. Then a check is performed to see that the frequency of the signal found via FFT is at least 4X higher than the next highest peak in the spectrum. If not, the signal is rejected. Another rejection criteria is based on bandwidth - i.e. if the particle velocity is 10 m/s but the range is limited to a lower value (say 8 m/s) so the resulting histogram is cut off, the higher speed particles will of course not be validated. There are additional validation criteria as the so called spherical validation which requires consistent

phases between detectors U1/U2 and U1/U3. Tolerance for this is set at about 10%. Further rejections occur if the particles are out of range on the low or high side.

Test Matrix

Three injectors were analyzed in this study. Apart from the DFI, two conventional diesel injectors were tested to establish a baseline for comparison - one piezo-electric injector (P/N 03L-130-277A) and one solenoid injector (P/N 03L-130-277N), both manufactured by Volkswagen. A summary of the experimental test matrix is shown in Table 2. The rail pressures selected were 200 bar, 300 bar, 400 bar and 500 bar for the conventional injectors. The DFI was tested first as a single-fuel injector (by sealing the secondary inlet) at pressures ranging from 100 - 300 bar, and then in its dual-fuel mode with the primary inlet pressure ranging from 100 - 300 bar, and the secondary inlet 25 bar higher than the primary pressure. Injection duration of 0.5 ms was chosen for the experiment. The different locations in the spray at which PDA

measurements were taken, are displayed in the sections below. Roughly 25000 samples were acquired at every measurement location for every experimental condition.

RESULTS AND DISCUSSION

High-Speed Imaging

Figures 6 and 7 show a comparison of the spray evolution from the two conventional injectors and the single-fuel spray of the DFI injector. The first two columns of images show the spray evolution of the conventional injectors (piezo-electric and solenoid respectively) while the third column of images is for the single-fuel injection mode of the DFI injector. Fig. 6 shows the spray evolution at 300 bar and Fig. 7 shows the same at 500 bar. The images displayed are chosen in particular to show the beginning stages of the injection event. The conventional injectors produce a spray with six individual jets, and as observed, from the images, have quite a wide spray cone angle, which would indicate a high lateral spray penetration length.

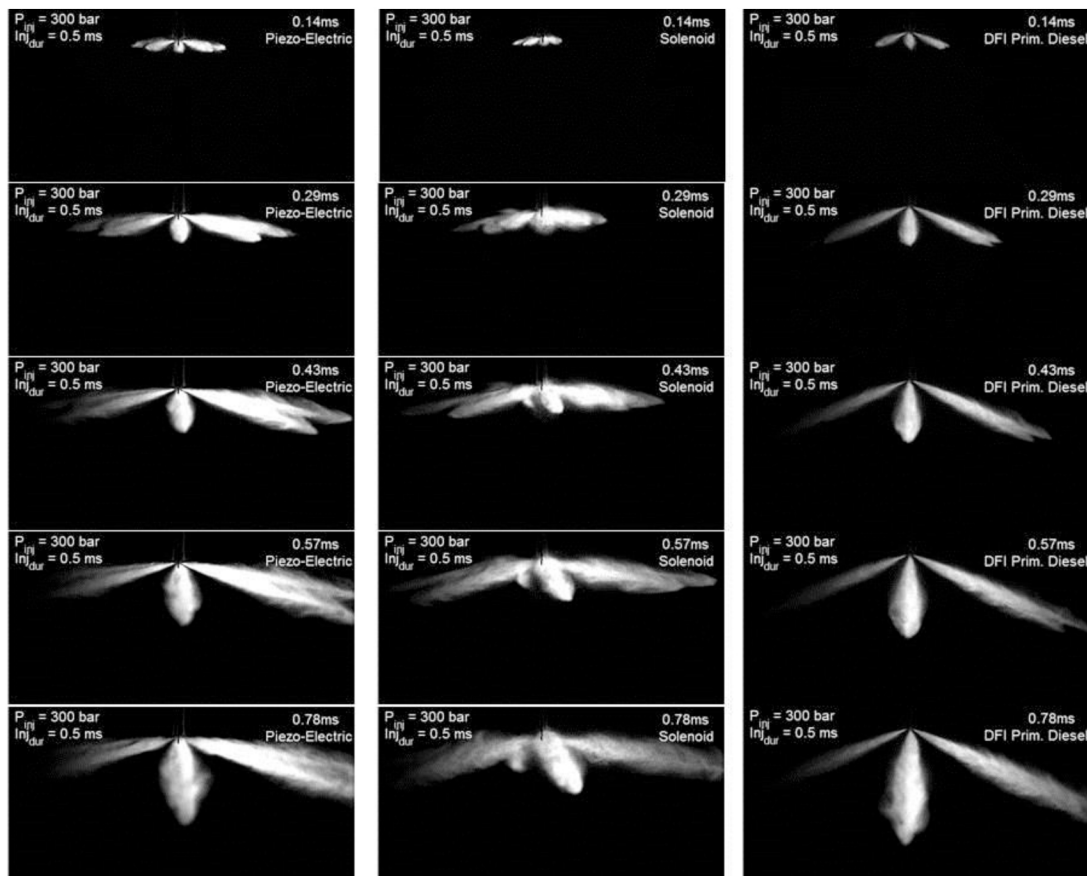


Figure 6. Conventional Injectors vs DFI Single Fuel Spray evolution at 300 bar