Effect of Injection Parameters and Injection System on Spray Characteristics for HSDI Diesel Engines

Essam M. EL-Hannouny and Patrick V. Farrell
Engine Research Center
University of Wisconsin-Madison, WI 53706

ABSTRACT

An experimental characterization of two high-pressure fuel injection systems has been conducted. The purpose of the study was to explore the effects of the injection system and the operating conditions on the spray characteristics for injection systems typical of a small bore diesel engine. One single and one double-guided multi-hole Valve-Covered-Orifice (VCO) type injector was used with a Common Rail (CR) injection system and two mini-sac injectors with different orifice diameters for a hydraulic electronic unit injection system (HEUI) were used. The diesel sprays were injected into a pressurized chamber with optical access at ambient temperature. The gas density inside the chamber was representative of the density in a High Speed Direct Injection (HSDI) diesel engine at the time of injection. The measured spray parameters included: injection pressure, injection duration, nozzle type, and nozzle diameter. Images of the transient sprays were obtained with a high-speed digital camera. From these images, spray tip penetration and cone angles were obtained directly. Moreover, spray droplet sizes averaged over the entire spray (SMD) were derived from the images using the Light Extinction Method (LEM).

1 Introduction

Direct Injection (DI) diesel engines generally offers an improvement in efficiency over indirect injection (IDI) systems, so this type of injection seems to be favored among high-speed diesel engine manufacturers. Increasingly stringent emissions regulations as well as fuel economy demands means that diesel engines will have to incorporate new fueling technologies to achieve these goals. In order to increase engine efficiency and reduce emissions, great attention has been focused on improving fuel atomization. Raising fuel injection pressure has been found to be effective in promoting fuel/air mixing, [1]. The mixture formation between the fuel spray and air is a governing process of combustion in the DI diesel engine, which affects the subsequent ignition characteristics, combustion rate, and exhaust emissions. Therefore, precise control over the fuel injection and thus the spray formation is essential in controlling the combustion process. The purpose of the study was to explore the effects of hole size, injection pressure, and injection system on the spray characteristics of a direct injection small bore diesel engine.

2 Experimental Setup and Diagnostics

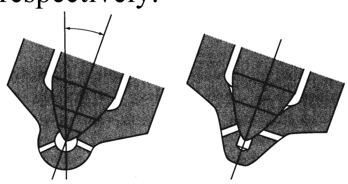
2.1 *Fuel injection systems*

To study the characteristics of transient diesel sprays injected from a multi-hole nozzle with high pressure, two different experimental fuel injection systems were used. The first one is a common rail (CR) system and the second system is a hydraulic electronic unit injection (HEUI) system.

Both systems can control the injection pressure independent of engine load and speed, and each has flexible injection timing.

2.1.1 *CR System* – This system contained three major sub-systems: a fuel pumping system, an injector and an electronic control system. Examples illustrating recent increasing interest in common rail injection systems may be found in [3]. The injectors tested with the CR were VCO type with different nozzle diameters.

2.1.2 *HEUI System* This system contained four main components: the injector, high-pressure oil system, a fuel system, and the injector control panel. The HEUI was initially developed for a heavy-duty diesel engine [4] them made into a smaller model for HSDI engines. The high-pressure oil system provides high-pressure oil to the manifold for the injection energy. The HEUI uses a hydraulic pressure intensifier system in the injector with approximately 7:1 pressure ratio to generate the fuel injection pressure. The HEUI injectors used in the experiments were mini-sac type with different nozzle diameters. Figure 1 and Table 1 illustrate the two types and the test matrix for the experiments respectively.



VCO Mini-sac

Figure 1 Nozzle configurations for tested injectors [2].

Table 1 Summary of nozzle geometry and test conditions

Injector type	**Mini-sac**	**VCO**
Guide type	Single	Dual, Single
Injection system	HEUI	CR
Injection angle (^{o})	145	130
Number of holes	6	6
Hole diameter (mm)	0.158, 0.165	0.160, 0.174
Convention (name)	HEUI158 HEUI165	CR160 CR174
Injection pressure (MPa)	33 to 160	33 to 130
Injection duration	Varied	Varied
Ambient density (kg/m^3)	18	18

2.2 *Spray diagnostics*

An optical setup is arranged to visualize the injecting spray for both injection systems. Figure 2 shows a schematic arrangement of the optical system, which consists of a laser light source, lenses and mirrors, a see-through spray chamber, and a high-speed camera. The laser source was a pulsed copper-vapor laser with 510.6 nm (green) and 578.2 nm (yellow) wavelengths. The duration of each laser pulse is 10-40 ns and the average energy per pulse is 2 mJ. The available range of pulse frequencies is 8-14 kHz using the internal trigger mode. The lenses and mirrors are arranged to fit a space limitation and to achieve the requirements of an incident light extinction principle. A gray step-tablet made of 11 neutral density filters is used for calibration of the image pixel values. The pinhole after the spray chamber is positioned at the focal point of the focusing lens to block the scattered light from a spray and allow only un-scattered light to the camera. The spray chamber provides an environment with high gas pressure and high gas density at room temperature. The injector is mounted on one end with a 65^{o} inclined angle for the common rail, which allows one of the spray plumes from a 130^{o} injection angle nozzle to be perpendicular to the light beam path. Different end plates were designed to fit different injectors with different injection angles. The high-speed digital camera used in this study was a Kodak (Model 4540) digital high-speed motion analyzer. A speed of 4500 frames/sec was used to get digital images containing 256 x 256 pixels and 8 bits of gray level.

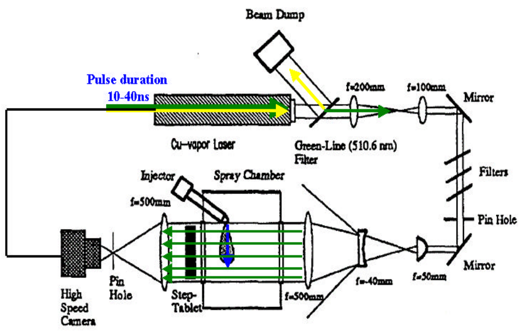


Figure 2 Schematic diagram for the spray diagnostics

2.3 *Image analysis*

The macroscopic features of the spray such as spray tip penetration, cone angle, and overall shape, can be determined directly from the TIFF images obtained with the digital camera. The microscopic structure, such as the droplet mean diameter of the spray must be calculated or estimated. The gray level of a pixel is proportional to the transmitted light intensity in the TIFF images; this information can then be used to estimate the overall spray Sauter Mean Diameter (SMD). A light extinction method (LEM), has been developed and used to measure SMD in diesel sprays in this way by several researchers [5,6]. Basic assumptions employed include: an axisymmetric spray pattern, a fixed, known spray droplet size distribution function, spherical droplets, constant index of refraction, no multiple scattering when light passes through the spray field, and no light absorbed by the spray droplets. More detail of the implementation of the calculation routine is given by [5]. A computer program was developed to aid in the image analysis process. This program provides a repeatable method of analysis, which eliminates some of the inherent errors associated with determining penetration and cone angles “by hand”. It also provides a good interface for using the LEM to determine overall average spray SMD.

3 Results and Discussion

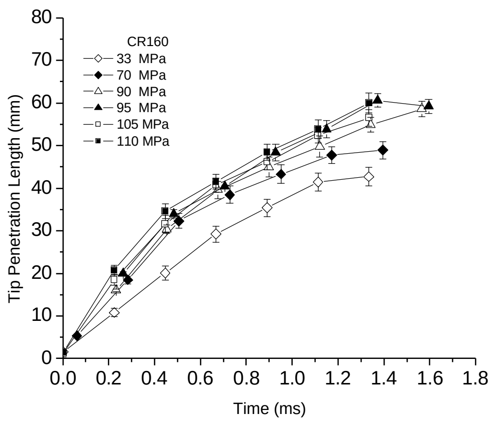
3.1 *Effect of injection pressure*

Figure 4 shows the effect of injection pressure on measured spray characteristics at a chamber density 18 kg/m^3 and constant mass delivery of 34 mm^3/st for CR160 nozzle. Figure 4a shows that higher injection pressure results in a longer spray tip penetration length due to higher momentum, which causes the jet to penetrate further in the chamber. The effect of the injection pressure gets smaller at higher pressures. The typical 95% confidence levels for each case are shown to show the shot-to-shot variation of three replicates. Figure 4b illustrates the effect of the injection pressure on the spray cone angle. The variations of cone angle with time throughout the spray event are not surprising due to the transient nature of the diesel spray and the gas entrainment during injection. The variation of initial spray angle with pressure, particularly for the 70 MPa case is a little surprising, particularly as the next lower pressure (33 MPa and the next higher pressure (90 MPa) show smaller initial spray angles. Figure 4c shows the effect of the injection pressure on the ROI (rate of injection) for the CR160 injector. At constant total mass delivery, the solenoid has to cut the duration short to keep the same total mass injected. Figure 4d shows the time history of the overall SMD for the CR160 nozzle. By increasing the injection pressure, the SMD decreases. According to breakup theory, higher injection pressure provides more energy and higher momentum due to the higher injection velocity, which results in smaller droplet sizes. However, the SMD trend shows that the change of droplet sizes becomes smaller as the injection pressure increases.

3.2 *Effect of nozzle size*

Figure 5a shows a comparison of the rate of injection for the same total mass delivery at 90 and 110 MPa for the CR160 and CR174 injectors. It is apparent from this figure that a bigger hole delivers more fuel in the early part of the injection and then closes faster to keep same the mass injected. From the results of Fig. 5 the smaller hole size nozzle has a shorter spray tip penetration, a wider spray angle, and a similar (90 MPa) slightly smaller (110 MPa) overall average SMD. The smaller sized droplets hold less momentum even though they were injected at the same pressure and as a result these droplets penetrate less into the air.

The two different types of injectors have different nozzle sizes and different overall cone angles as shown in Table 1. These effects cannot be separated, given the injectors available. However, Su [7] investigated the effect of cone angle at 25% load for different shape inlet nozzles with the same nozzle diameter and two different cone angles (125^{o} and 145^{o}). Su reported that the cone angle has a small effect on the tip penetration, spray angle and SMD. The effect of the nozzle size on the spray parameters, in this study, is likely to override the effect of the cone angle at 45% load as shown in Fig. 5 [8].



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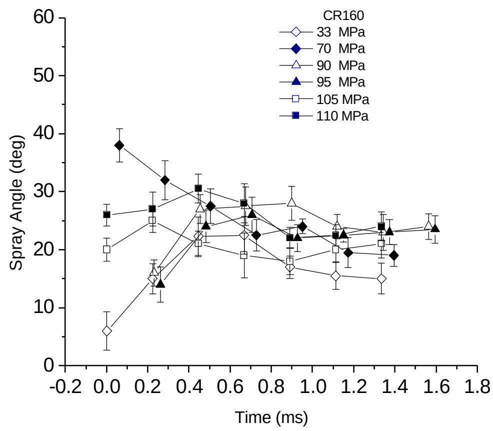

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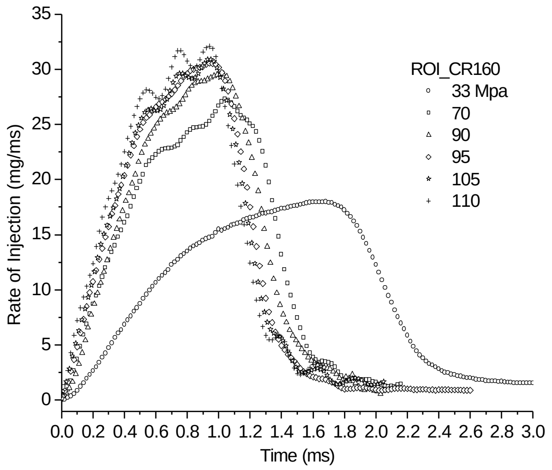
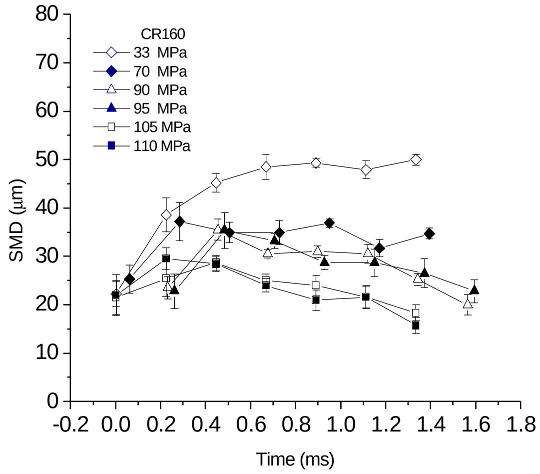
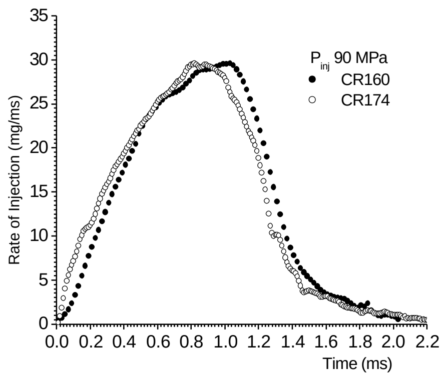


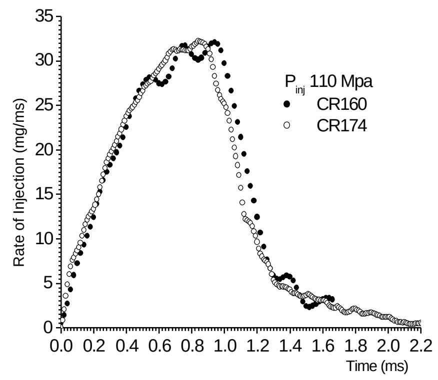


(c) (d)

Figure 4 Effect of injection pressure on the spray characteristics for CR160 (a) tip penetration, (b) spray angle, (c) Rate of injection and (d) SMD (at 34mm^3/st delivery and 18 kg/m^3)

(90 MPa) (110MPa)





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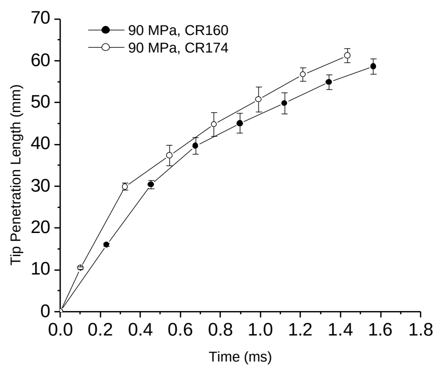

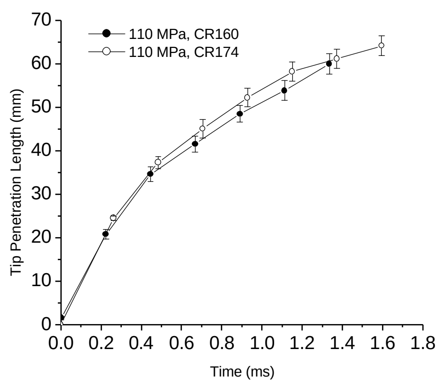

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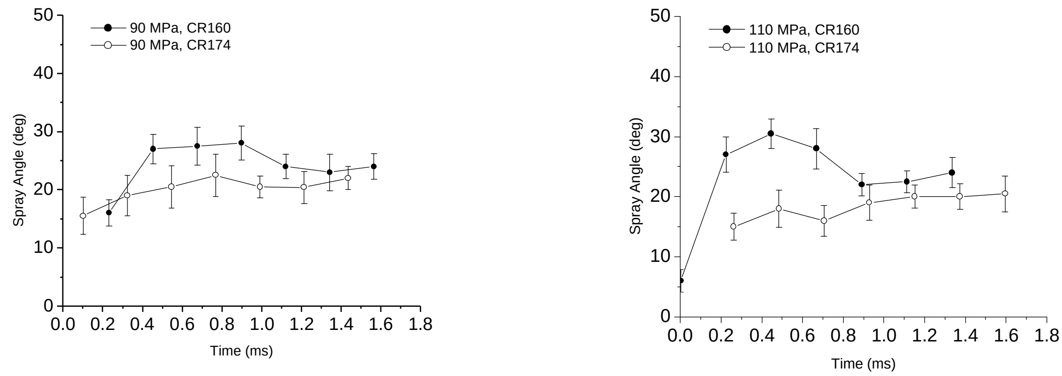

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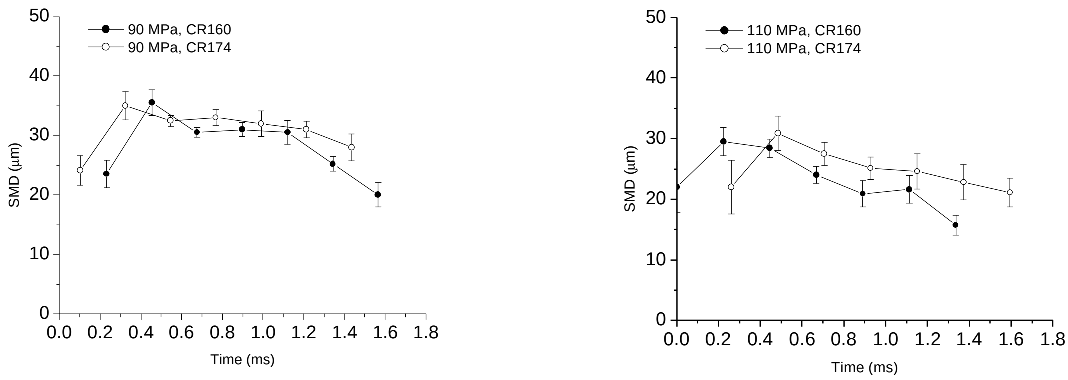
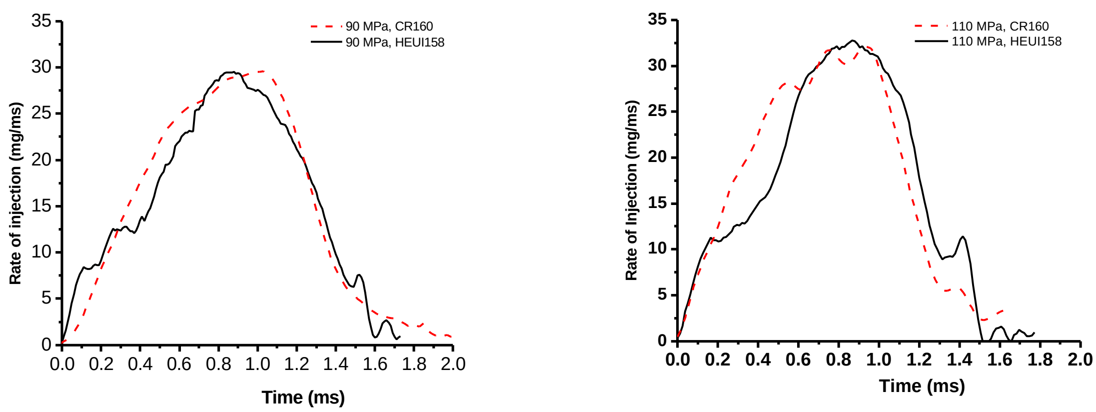


(d)

Figure 5 Effect of nozzle size on the spray characteristics for CR160 and CR174 at 90 and 110 MPa injection pressures (a) Rate of injection (b) penetration, (c) spray angle, and (d) SMD (at 34mm^3/st delivery and 18 kg/m^3)

(90 MPa) (110 MPa)



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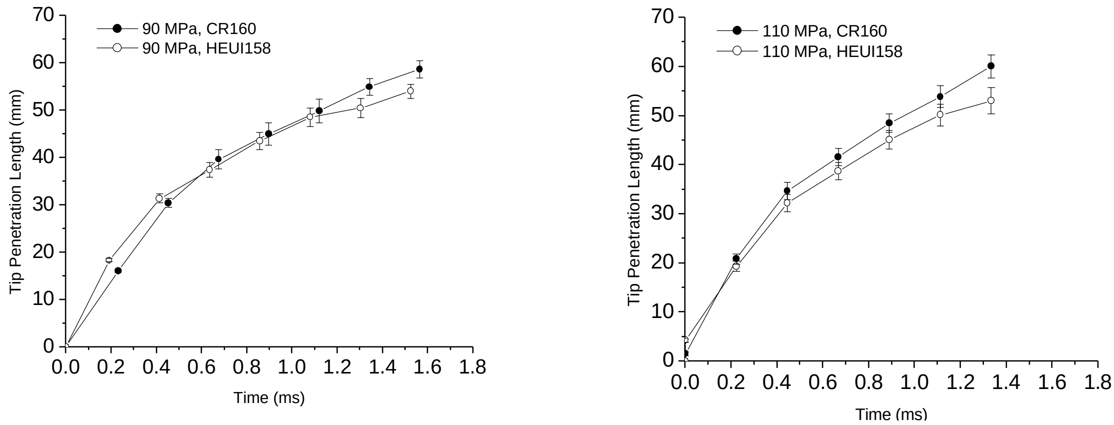

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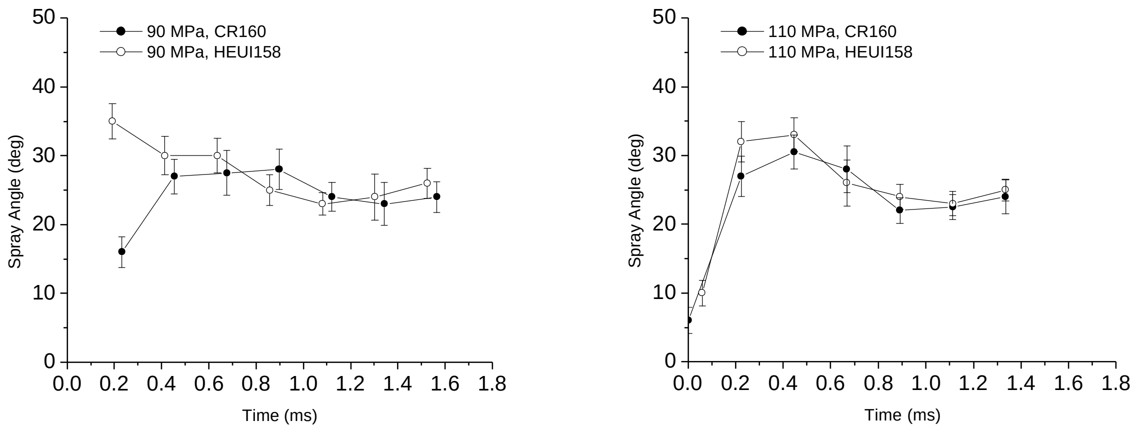

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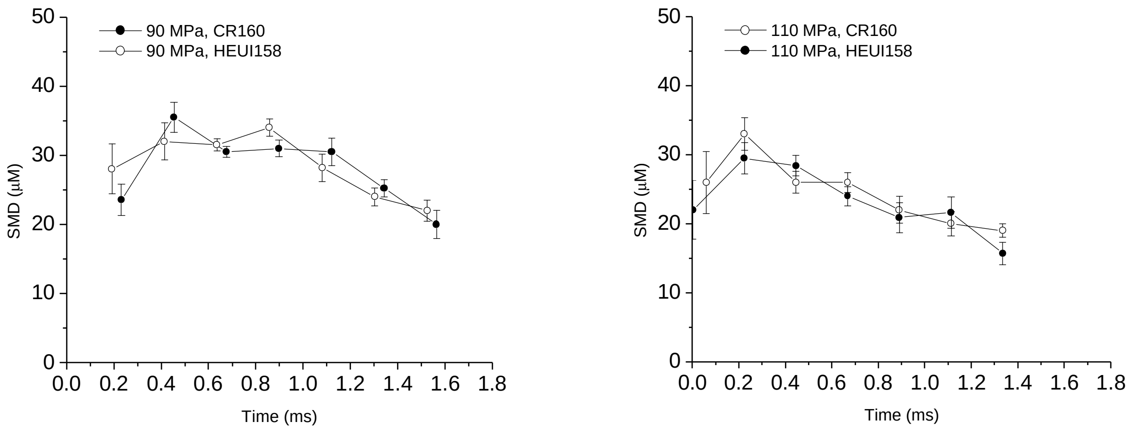

(d)

Figure 6 Effect of injection system and nozzle tip on the spray characteristics at 90 and 110 MPa injection pressures for CR160 and HEUI158 (a) Rate of injection (b) penetration, (c) spray angle, and (d) SMD (at 34mm^3/st delivery and 18 kg/m^3)

3.3 *Effect of injection system and nozzle tip type*

Figure 6 shows the comparison between HEUI158 and CR160. The ROI shape in Fig.6a shows that HEUI with the mini-sac tip has a lower injection rate during the initial period and almost the same ending slope for both injection pressures. Based on the results of Fig. 6 the two nozzles have mostly the same tip penetration, spray angle, and a same overall average SMD. Differences include the substantially larger initial spray angle for the HEUI158 system at 90 MPa and the CR160 penetrates a little further than the HEUI158 at 110 MPa. It can be concluded from Fig. 6 that the combined effect of the injection system and the tip primarily affects the ROI, but only has a minor effect on spray penetration, spray angle, and SMD.

4 Conclusions

Characterization of high injection pressure diesel sprays for HSDI engines was performed based on high-speed photography and light extinction techniques. The effects of injection pressure, nozzle size and injection system on spray characteristics were investigated. Higher injection pressure produced smaller SMD values, longer spray tip penetration and had small effect on the spray angle. For the range of nozzle sizes as well as cone angles investigated, the effect of nozzle size on the spray characteristics was larger than the effect of nozzle cone angle. In other words the dominant variables that influence the droplet size are injection pressure and nozzle size. The CR and HEUI fuel systems provide flexible control for the injection parameters for the present small diesel engine but brought the technical challenge of optimizing the additional variables.

Acknowledgments

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