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Impact of fuel spray angles and injection timing on the combustion and emission characteristics of a high-speed diesel engine

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A B S T R A C T

This paper presents effect of fuel spray angles such as narrow (60°) and conventional (156°) spray angles on spray behavior, combustion and emissions characteristics. To achieve research objectives, fuel spray images measured using a visualization system and two injectors at spray angles of 60° and 156° were analyzed for spray tip penetration and spray development processes as a function of injection timing and injection pressure. The spray angle effects on combustion and emission characteristics, and engine performance were analyzed.

Results revealed that 60° injector exhibited higher maximum combustion pressure, higher maximum heat release rate, and lower ignition delay than 156° injector. Under various injection timings with 156° spray angle, it is shown based on the experimental results that peak value of combustion pressure decreased when injection timing of 30° BTDC (before top dead center) was advanced. Regarding emission characteristics, the use of narrow spray angle injector is advantages in case of an early injection combustion strategy because it yields low ISHC (indicated specific hydrocarbon), ISCO (indicated specific carbon monoxide), and $ISNO_x$ (indicated specific nitrogen oxides) emissions. In addition, the IMEP (indicated mean effective pressure) in a narrow spray angle injector is higher than that in conventional spray angle injector.

1. Introduction

The demands for diesel engines has been increasing because of their higher thermal efficiency compared to gasoline engines. However, NO_x (nitrogen oxides) and PM (particulate matter) from the combustion process of diesel engines have raised concerns related to environmental pollution and conservation. In order to reduce the atmospheric contamination due to exhaust gases from automobiles, international emission regulations have increasingly become more stringent. Therefore, various eco-friendly combustion technologies, such as the use of alternative fuels (biodiesel [1,2], dimethyl-ether [3–5], bioethanol [6,7] etc.), RCCI (reactivity controlled compression ignition) [8], and LTC (low temperature combustion) [9,10], in a diesel engine have been actively studied by many researchers to reduce exhaust emissions while maintaining combustion performance.

In high-speed direct injection diesel engines, the atomization characteristics of fuel spray play an important role in the combustion characteristics because the formation process of a mixture between the atomized spray and the entrained air have direct influence on the emission formation and combustion performance. The common-rail injection system, consisting of a solenoid type injector and a high pressure chamber, show good performance in regard to the fast response time and fuel atomization. In addition, the injection timing and spray angle have a great influence on the combustion and emission characteristics in a common-rail diesel engine because the targeting points at the surface of the piston bowl are determined by the spray angle and the injection timing. Mobasheri and Peng [11] revealed that the narrow-spray-angle injector can reduce the NOx and soot emission without the deterioration of fuel consumption because of the improvement of the air-fuel mixture quality. Yoon et al. [12] researched the effect of the spray angle and injection strategy on the combustion of DME (dimethyl ether), its emissions, and particle size distribution

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Nomenclature

m_{fuel}	fuel mass (mg)
P_{amb}	ambient pressure (bar)
P_{inj}	injection pressure (bar)
τ_{asoe}	time after start of energizing (ms)
τ	injection timing (ms)
θ	crank angle (°)

characteristics in a common-rail diesel engine. The results revealed that the combustion pressure from single combustion for narrow-angle injectors (60° and 70°) increased, with advanced injection timing compared to the results of the wide-angle injector (156°). In the diesel engine system, the spray targeting point is very important because wall wetting of the injected fuel causes UHC (unburned hydrocarbon), and the degree of utilization of oxygen in the combustion process highly depends on the targeting point [13–15]. In addition, combustion performance deteriorates, and knocking and large amounts of NO_x emissions are caused by rapid combustion in the fuel-rich regions. Therefore, investigations have been carried out by various researchers [16–19] that aimed the determination of the optimal spray angle. Fang et al. [19] reported that narrow angle injector with a 70° spray angle resulted in higher soot emissions due to the fuel film deposition on the piston wall, and in lower NO_x emission due to the rich air/fuel mixture near the piston bowl wall. The ignition timing and combustion characteristics in the diesel combustion process are also significantly affected by the injection timing. Recently, researches [20–24] examined various injection timings as well as very early- and late-injection timings, and have studied the reduction of exhaust emissions using methods such as the HCCI (homogenous charge compression ignition) and LTC. Saravanan et al. [21] revealed that a decrease in NO_x emission without deterioration of smoke emissions can be achieved by the retardation of injection timing. However, they reported that the brake thermal efficiency was slightly decreased by the retardation of the injection timing. In the research study of Kannan and Anand [22], it was revealed that the brake thermal efficiency was improved, and the reduction of NO_x and smoke emissions could be achieved by employing advanced injection timing with a high injection pressure.

In this paper, the effects of spray angle and injection timing on combustion and exhaust emissions characteristics are experimentally investigated in a single cylinder diesel engine. In particular, broad test ranges are used for the injection timing, with values of 40° BTDC (before top dead center) to TDC (top dead center). In addition, the spray behavior under different injection and ambient pressures is studied to obtain an accurate understanding of combustion and emission characteristics.

2. Experimental setup and procedure

2.1. Spray visualization system and image analysis procedure

The spray visualization system consists of a high speed camera (Fastcam APX-RS, Photron), metal-halide lamps (HVC-SL, Photron), a fuel injection system, and the spray image storing devices, as illustrated in Fig. 1. These were needed in order to measure the spray characteristics from two diesel injectors at different spray angle. In this study, two injectors were utilized with spray angles of 156° and 60°. Based on the 156° spray angle injector (conventional injector), the characteristics of the 60° spray angle injector (narrow angle injector) were investigated. For spray visualization, test injectors were operated as solenoid types, and they were controlled by the injector driver (TEMS, TDA-3200A). The synchronization between the injector and high speed camera are realized by a digital delay/pulse generator (Model 555, Berkeley Nucleonics Corp.). The generated spray images acquired at different spray angles were stored in a data acquisition system with an image grabber. To clarify the spray characteristics, the diesel spray images acquired from the injectors were captured from the bottom side. The test injectors were installed onto the high pressure chamber. The high pressure chamber was pressurized by nitrogen gas to simulate ambient pressure conditions.

In this study, the spray tip penetration was calculated based on the conversion of values obtained from the projected images, because the spray images were captured as a bottom side view. The conversion procedure is as follows: (a) Measurement of spray tip penetration from the projected images, (b) Calculation of the conversion factors according to the spray angle, (c) Conversion of the measured spray tip penetration using the conversion factors.

$$\text{Real spray tip penetration} = \text{Projected spray tip penetration} \times \text{Conversion Factor} \quad (1)$$

The conversion factors for the 156° and 60° injectors are 1.022

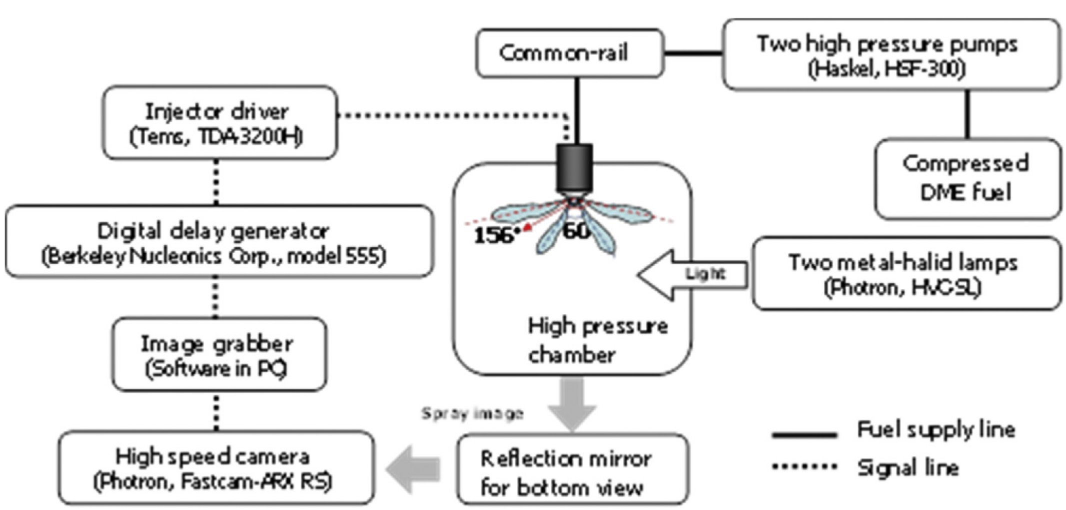

Fig. 1. Schematic of the diesel spray visualization system.