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Effects of injection strategy and coolant temperature on hydrocarbon and particulate emissions from a gasoline direct injection engine with high pressure injection up to 50 MPa

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ABSTRACT

The present study investigated the effect of coolant temperature, injection pressure, and injection timing on emissions in a gasoline direct injection (GDI) engine. Two coolant temperatures of 40 °C and 80 °C, and wide range of injection timings from before top dead center (BTDC) 360° to BTDC 210° were tested under injection pressures in the range of 5 MPa–50 MPa. Particle number (PN), soot, total hydrocarbon (THC), and nitrogen oxides (NOx) were measured under the various experimental conditions. In addition, the spray and flame images were used to observe the spray-wall interaction and to identify the existence of a fuel film.

Experimental results showed that the increase in injection pressure significantly reduced the particulate emissions, especially for the wall wetting condition (BTDC 330°). The PN emissions from the wall wetting condition was reduced by about 90% by increasing injection pressure from 10 MPa to 50 MPa. Furthermore, increasing the coolant temperature was an effective way to reduce the PN, soot, and THC. In particular, the THC was reduced by about 30%, while the change in injection pressure and injection timing varied by only 10%.

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1. Introduction

Particulate emissions have not been a big issue in gasoline engines, because the premixed combustion does not generate as much particulate emissions as the diffusion combustion of diesel engines. However, many studies have shown that gasoline direct injection (GDI) engines emit much more particulate emissions than port fuel injection (PFI) engines [1]. Thus, the particulate matter (PM) and particle number (PN) began to be regulated for gasoline engines in the Euro 5 and Euro 6 emission regulations, respectively.

GDI engines have increased the fuel injection pressure to meet the emission regulations by improving fuel atomization. Since most GDI injectors and fuel pumps are not capable of using an injection pressure above 20 MPa, the maximum injection pressures applied to GDI engines were usually 20 MPa [2]. Limited research groups could apply a higher injection pressure, and the maximum injection pressure reported in papers was about 30 MPa [3]. These studies demonstrated that increasing the injection pressure was an effective way to reduce the hydrocarbon (HC) and particulate emissions. Choi et al. [4] showed that increasing the injection pressure from 4 MPa to 10 MPa reduced PM and total hydrocarbon (THC) by 75% and 10.3%, respectively. However, as the injection pressure increased more, the amount of emission reduction decreased. Matousek et al. [5] showed that increasing injection pressure from 10 MPa to 20 MPa reduced the PN by 70% on average, but an injection pressure increase from 20 MPa to 30 MPa reduced the PN by only 50% on average. In other words, even though many injector manufacturers have been developing injectors that use the higher injection pressure, at some point, increasing the injection pressure would not reduce the particulate emissions any more. Therefore, an investigation of the effect of the additional increase in injection pressure up to 50 MPa on the emission reduction is required.

Besides fuel atomization, fuel film is another important factor for particulate emissions. A fuel film is formed when the injected fuel impinges on the piston head, and this is a major source of

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particulate emissions and HC [6]. Many studies have applied various engine operating strategies to reduce the fuel film. He et al. [7] suggested several engine operating strategies to minimize PN in a GDI engine, and the first strategy was to retard the injection timing to avoid spray-wall interaction. The authors conducted a start of injection (SOI) sweep from before top dead center (BTDC) 301° to BTDC 209°. However, since only low injection pressures under 10 MPa were applied in this study, further investigations on how the spray-wall interaction would affect the particulate emissions under higher injection pressure conditions are required. On the other hand, some researchers evaporated the fuel film faster by increasing wall temperature and injection pressure instead of avoiding the wall wetting. Pan et al. [8] observed the fuel film using a CCD camera and a sapphire plate, and identified that the thickness of fuel film was reduced with increasing wall temperature. In addition, Schulz et al. [9] measured wall temperature using an IR camera and showed that an increase in injection pressure decreased the maximum wall temperature reduction. That is, less fuel film was formed at a higher injection pressure. However, since these studies were conducted in the atmosphere but not in an engine cylinder, it was not determined how the increase in temperature and injection pressure affected the emission reduction. Therefore, it is required to investigate the effect of injection pressure and coolant temperature on the emissions of a GDI engine.

In summary, since the most important subject recently issued in the automotive area is emissions, especially the particulate emissions, it is required to study the engine operating strategy to reduce the emissions in GDI engines. Although the effects of injection pressure, injection timing, and coolant temperature on emissions have been investigated in many studies, further investigation should be conducted in a real engine condition using the higher injection pressure. Therefore, the present study compared the effect of coolant temperature, injection pressure, and injection timing on the emissions in a GDI engine.

2. Experimental apparatus and test conditions

2.1. Experimental apparatus

The experimental setup is illustrated in Fig. 1. A single-cylinder GDI engine was used as a test engine. Gasoline was supplied using an air-driven liquid pump because it was difficult to find a commercial high-pressure gasoline pump that supplies 50 MPa. The GDI injector used in the present study was a multi-hole injector with six nozzle holes. The injector was mounted between two intake valves, and a spark plug was mounted in the center of the cylinder head. Detailed specifications for the engine are listed in Table 1. The amount of fuel injection and intake flow rate was controlled using a mass flow meter and an oxygen sensor. The intake flow rate was monitored by the mass flow meter located at the intake port, and a throttle valve was controlled in real time to maintain the flow rate at 130 LPM. The injection duration was controlled under the stoichiometric combustion condition in real time. Therefore, the fuel injection mass was the same for all the experimental conditions.

PN and soot were measured using a Pegasor PPS-M and the AVL smoke meter (AVL-415S), respectively. The measurable concentration range of the PPS-M is from about 0.01 to 250 mg/m^3, and the detectable particle size range is from a few nanometers to 2.5 µm. THC and NOx was measured using an exhaust gas analyzer (MEXA-9100, Horiba). Emission data were acquired under steady state after sufficient operating time for all the experimental conditions. Detailed specifications for the emission measurement devices are summarized in Table 2.

The present study also observed the fuel spray and flame propagation in the cylinder using an optical engine and a high-speed camera (Photron Mini AX100). Fig. 2 shows the optical engine setup and sample images of spray and flame. As shown in the figure, the spray was observed from the side view, and the flame was observed from the bottom view. A metal halide lamp was used to observe the spray development. There was no additional light source except for the chemiluminescence of the natural flame. The size of the side view window was 49 mm × 34 mm, and the diameter of the bottom view window was 55 mm, which is about 71% of the bore. The spray images were used to identify the effect of injection timing and coolant temperature on the spray development, and the flame images were used to compare the amount of fuel film on the piston surface.

2.2. Experimental conditions

The engine was operated at 1500 rpm, and the intake flow rate was 130 LPM for all the test conditions. Fuel mass was 14.145 mg/stroke under stoichiometric combustion condition. The nominal indicated mean effective pressure (IMEP) was about 0.52 MPa at the minimum advance for best torque (MBT). There were three main operating parameters: injection timing, injection pressure, and coolant temperature. A wide range of injection timings from BTDC 360° to BTDC 210° were applied to investigate the effect of injection timing and wall wetting on the emission characteristics. The injection timing after the BTDC 210° was not applicable because the short time interval between the injection and ignition made the combustion unstable. For typical GDI engines, the injection timing is in the range of BTDC 330° to BTDC 240° for homogeneous combustion.

The injection pressure was varied from 5 MPa to 50 MPa (5, 10, 20, 33, 50 MPa). The 33 MPa was chosen because it is the maximum operating condition proposed by the injector manufacturer. The injector can withstand up to 50 MPa, but the injector manufacturer does not guarantee its lifetime at the injection pressure higher than 33 MPa. As the injection pressure increases, the injection rate also increases. The fuel mass was controlled by adjusting the injection duration. The injection duration was changed based on the equivalence ratio measured by an oxygen sensor. A higher injection pressure is expected to increase fuel atomization and improve air–fuel mixture homogeneity.

Two coolant temperature conditions of 40 °C and 80 °C were applied. The 40 °C conditions are slightly different from a cold start condition. Under the cold start conditions, the in-cylinder temperature increases until the heat loss and supply are balanced and the engine reaches steady state. In the present study, however, all the emission and combustion data were measured under steady state conditions. Nevertheless, a higher coolant temperature generally promotes fuel evaporation [10], so the particulate emissions are expected to be reduced. In the present study, the effects of these three experimental parameters on the emissions were compared. The experimental conditions are summarized in Table 3.

3. Results and discussions

Fig. 3 shows PN, soot, THC, and NOx emissions for the various injection timings. The injection pressure was 33 MPa, and the coolant temperature was 40 °C. Data were normalized based on the emission values of the BTDC 330°. As shown in the figure, the PN and soot were highly dependent on injection timing. The early fuel injection conditions prior to BTDC 330° resulted in about 10–20 times higher particulate emissions than the late fuel injection after the BTDC 300°. For the early injection timing conditions, the normalized PN was around 1.0–1.3. However, as the injection timing was retarded after BTDC 300°, the PN converged below 0.06.

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