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Research Paper

The dual-port fuel injection system for fuel economy improvement in an automotive spark-ignition gasoline engine

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HIGHLIGHTS

- Dual port-fuel injection (DPI) for a spark ignition engine.
- High-speed camera visualized the wider spray angle of the DPI system.
- The DPI improved fuel economy by 2.8%.
- The DPI reduced hydrocarbon in cold-start.

ABSTRACT

The purpose of the present study was to investigate the performance of the dual-port injection (DPI) system in an automotive spark-ignition engine. The DPI system utilizes two port fuel injection (PFI) injectors per cylinder, i.e., one injector at each intake port. An original 4-cylinder PFI engine head was modified to accommodate total 8 PFI injectors. In the present study, three spray angles and two install configurations were investigated in the intake port visualization, steady-state part-load experiments, and cold-start experiment. The intake port spray visualization experiment showed that the wider fuel spray provided better fuel distribution, but also more wall wetting. The steady-state engine experiment at the several critical part-load conditions showed that the DPI system in combination with the open-valve-injection strategy achieved the most brake specific fuel consumption (BSFC) reduction of 4.6%. The average BSFC reduction of the 9-point experiment was 2.8%. The cold-start experiment also showed a fuel economy gain by the DPI system. In the cold-start experiment the wider spray angle exhibited higher total hydrocarbon emission likely due to the greater wall wetting observed in the intake port spray images.

1. Introduction

The port-fuel injection (PFI) system has been widely used in gasoline engines and well established through decades of improvement. Although the gasoline direct-injection (GDI) system seems to be in favor recently for many profound reasons, interests in the PFI system has been resurfaced due to its superiority in particulate number (PN) emission reduction. Studies [1,2] found the substantial amount of particulate matter emission from GDI engine. Some researches [3,4] suggested fuel blending with either gaseous or higher-octane number fuels to enhance combustion and emission reduction in gasoline engines. In addition, the cold-start performance has been more critical due to more frequent engine restart situation in some advanced powertrain applications, such as the stop-start feature and the hybrid powertrain system. Gasoline PFI engines tend to exhibit high CO and HC due to rich air/fuel mixture, lower catalyst conversion efficiency, and poor fuel economy due to increased friction and incomplete combustion during the cold-start period [5,6]. Therefore, efforts have been made to

Abbreviations: PFI, port-fuel injection; GDI, gasoline direct-injection; PN, particle number; PDI, port and direct injection; BSFC, brake specific fuel consumption; BMEP, brake mean effective pressure; DPI, dual-port injection; CVVT, continuous variable valve timing; IVO, intake valve opening; aTDC, after top dead center; CVI, closed valve injection; OVI, open valve injection; bTDC, before top dead center; CA, crank angle; EOI, end of injection; BSCO, brake specific carbon monoxide; NOx, nitric oxides; THC, total hydrocarbon; CO, carbon monoxide; BSNOx, brake specific nitric oxides

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improve the PFI gasoline engines with the advanced injection systems.

Ikoma et al. [7] investigated one of the advanced injection concepts, namely, the port and direct injection (PDI) system. A PFI injector was installed on the intake port of each cylinder in a GDI engine. The brake specific fuel consumption (BSFC) reduction of the PDI system was as high as 7% at 1200 rev/min and 650 kPa brake mean effective pressure (BMEP) with the optimal injection ratio between two injectors. BSFC is the ratio of fuel consumption to the brake power, developed as a measure of fuel economy of internal combustion engines. It is often expressed in g/kWh. It was concluded that the fuel economy improvement was limited to the medium load condition. As a matter of fact, Iorio et al. [8] showed that the PDI system exhibited lower particulate number emission, but fuel economy improvement was negligible at high load conditions. Turbulence intensity enhancement by the in-cylinder geometry optimization [9] may require to improve the performance of the PDI system. On the other hand, the PDI system has shown promising results in the dual-fuel applications [10–13] and the advanced combustion regimes [14,15]. Nevertheless, the PDI system is likely one of the most expensive injection systems for improving SI engines whether compared to the PFI or GDI system.

The dual-port injection (DPI) system is another promising strategy for fuel economy improvement and THC reduction in gasoline engines. The DPI system employs two PFI injectors on each cylinder. The injectors can be installed at the downstream of the intake port after the split. Locating the DPI injectors at the proximity of intake valves allows fuel spray to directly aim at the top of intake valves. Benefits from this design can be maximized with fuel injection during the intake valve opening. In particular, injecting fuel after the closure of the exhaust valves optimizes fuel delivery by minimizing the wall wetting and fuel lose during valve overlap, also known as a blow-through. This is in principle the injection strategy adapted in the current GDI engines operated under the stoichiometric condition. Instead of the sophisticated GDI injector and high-pressure pump, the DPI strategy requires only an additional PFI injector. The fuel vaporization and mixture quality of the DPI system should be competitive to those of the conventional PFI system. The DPI system might be the most cost-effective solution to achieve the performance equivalent to the GDI system, while maintaining the advantages of the PFI system, such as lower particulate emission [8,11], lower cost, and overall system simplicity.

In spite of the aforementioned advantages, the performance of the DPI system in a gasoline engine has not been investigated except for a couple of the dual fuel combustion studies [16,17]. The purpose of the present study was to investigate the performance of the DPI system in comparison to the standard PFI system in an automotive SI engine. This study focused on the fuel economy and THC emission of the DPI system under the critical part-load and cold-start operations. Three sets of PFI injectors with different spray angles were installed at two different angles in order to identify the optimal DPI system for the experimental engine.

2. Instrumentations

2.1. Spray visualization

A visioscope (R10-44, Everest VIT, U.S.A.) was installed on the intake port to visualize the fuel spray and mixing from the two PFI injectors of spray angles of 20° and 30°, namely N20 and N30, respectively. A high-speed camera (Fastcam SA3, Photron, U.S.A.) and metal halide lamp (BMH-350, HIBIKI, Japan) were employed for taking images at a sampling frequency of 1000 Hz. The image acquisition was initiated immediately after the engine start. The spray images were extracted from the recorded video files for comparison between the two different spray-angle injectors.

Table 1
Engine specifications.

Parameters			Units	Nominal values
Number of cylinders			–	4
Bore			mm	77
Stroke			mm	85.44
Displacement volume			cm^3	1591
Compression ratio			–	10.5
Injection type			–	PFI
Cam type			–	DOHC
Valve timings	Intake	Open	aTDC	−40 to 10
		Close	aBDC	13–63
	Exhaust	Open	aBDC	−40
		Close	aTDC	3

2.2. Engine experiment

The experimental engine was a 4-cylinder, PFI, spark-ignition gasoline engine. The displacement volume of the natural-aspired engine was 1591 cm^3. The details of the engine specifications are listed in Table 1. The engine was engaged with an eddy current dynamometer (SE250, Dasan, South Korea) that was capable of absorbing the engine power up to 250 kW. The base engine was equipped with the continuous variable valve timing (CVVT) system on the intake cam, which can adjust the intake valve opening (IVO) timing between −40° and 10° after top dead center (aTDC). In the present study, the IVO timing was governed by the stock engine control unit.

Fig. 1 shows the difference in concepts between the conventional PFI and the present DPI systems. Two DPI engine heads were prepared for the two injector install angles, 48.5° and 51.5°. Fig. 2 illustrates the injector install angle with respect to the vertical centerline of the engine cylinder. The injector install angle of the stock PFI engine was 48.5°. The 51.5°-install angle was designed to aim at the lower part of the intake valve head as illustrated in Fig. 3. The center-to-center distance between the two PFI injectors was 28 mm. A modified fuel rail accommodated 8 PFI injectors for the 4-cylinder DPI engine.

The stock PFI injector with a 4-hole nozzle and a spray angle of 15° served as a baseline in the PFI case. The PFI injectors in the DPI cases were equipped with an 18-hole nozzle. The spray angles of the three DPI cases were 20, 25, and 30° (referred to as N20, N25, and N30). The spray angle refers to an angle of the combined spray from all holes,

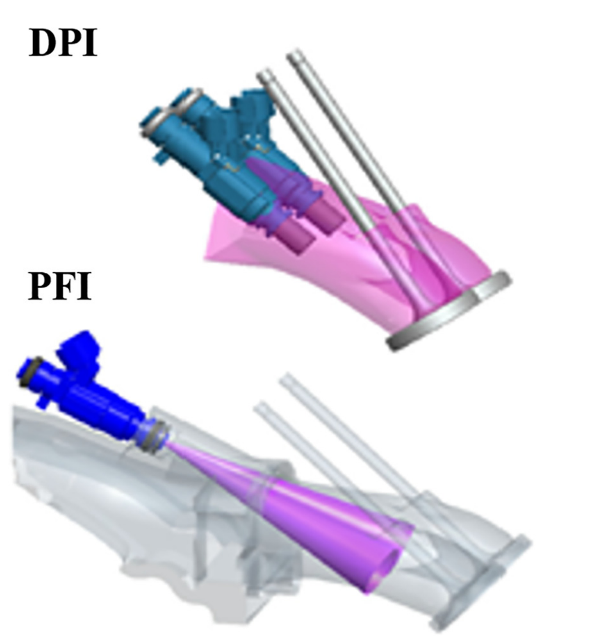

Fig. 1. Conceptual drawings of the PFI and DPI systems.