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Research Paper

Effects of the swirl ratio and injector hole number on the combustion and emission characteristics of a light duty diesel engine

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HIGHLIGHTS

- Effects of swirl ratio and injector hole number on combustion and emissions were studied.
- A single cylinder diesel engine and KIVA code were used.
- Correlations between swirl control valve and swirl ratio were calculated.
- PM and CO emissions were reduced with increases in swirl ratio and hole number.

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ABSTRACT

In this study, the effects of swirl and the injector hole number were investigated to enhance the mixing of fuel and air. Both experimental and analytical methods were employed. The KIVA code coupled with the CHEMKIN chemistry solver was used to analyze the swirl intensity at various angles of the swirl control valve and experimental results. For the experimental investigation, a 498.75 cc single cylinder engine and a 55 kW AC dynamometer were employed. The experiments were conducted at IMEP values of 6 and 10 bar with 7, 8, 9, and 10 hole injectors. The swirl intensity was varied by opening of the swirl control valve from 0° to 90°.

The experimental results demonstrated that the swirl intensity has an effect on the combustion and emission characteristics. An enhanced swirl intensity reduced the PM and CO emissions but increased the NOx emissions and ISFC. An increase of the injector hole number resulted in decreases of the PM and CO emissions along with a an increase of NOx emissions and no significant difference of output. However, the exhaust characteristics with the 10 hole injector deteriorated as the interference increased.

1. Introduction

Diesel was once regarded as an environmentally friendly automobile fuel because of its low CO_2 emissions, which is known as a greenhouse gas (GHG) [1]. However, due to high PM and NOx emissions, many issues have been raised [2]. As a result, regulations regarding exhaust gas have been continuously strengthened and in recent years, exhaust gas regulations for roads have been added. Accordingly, various studies have been conducted to reduce exhaust emissions to satisfy these regulations [3,4].

In the direct injection (DI) diesel engine, because fuel is directly injected into the cylinder at the end of the compression stroke, the time for mixing the fuel and air is very short. Thus, increasing the mixture of fuel and air improves the combustion and exhaust characteristics [5–9].

In this study, the effects of swirl and the injector hole number were investigated to improve the internal flow and the atomization characteristics of the fuel for better mixing [10,11]. Swirl, which is the rotary motion of the air about the axis of the cylinder, can be reinforced by increasing the flow rate of a pipe by attaching a valve to one of the two intake pipes. Previous studies have shown that increasing the swirl reduces exhaust emissions due to increased in-cylinder mixing [12–18], but decreases the power due to increased pumping losses and increased wall heat loss [19–21]. If the injector hole number is increased, the nozzle hole size decreases. As a result, the fuel injected per hole decreases and atomization characteristics are improved [22–25]. Therefore, the PM, THC, and CO emissions would be reduced with a higher injector hole number which has smaller hole sizes [14,25–27]. On the other hand, it is known that increasing the hole number causes worse

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fuel efficiency [28,29]. However, the distance between the plumes of injected fuel decreases and plume interference occurs as the swirl intensity increases. If plume interference occurs, a locally rich region is generated which adversely affects the exhaust characteristics [30]. Therefore, the purpose of this study was to investigate the influence of the swirl and injector hole number on a light duty diesel engine according to the load conditions.

In this study, experimental and analytical methods were applied simultaneously to investigate the influence of swirl and the injector hole number. The KIVA code was used to analyze the swirl intensity according to the angle of the swirl control valve with the full 360° mesh including the intake port and swirl control valve using ICEM-CFD which is computational grid generating tool and to analyze the experimental results. Experiments were conducted using a 498.75 cc single cylinder engine. In addition to the conventional 8 hole injector, the effects of the injector hole number were analyzed using 7, 9, and 10 hole injectors.

2. Experimental setup and test conditions

In this study, a manual swirl control valve (SCV) was used to control the swirl intensity. The valve was installed in one of the two pipes of the intake port to form a swirl flow and the opening degree was confirmed by a protractor installed on the right side. In this study, the intake port flow was modeled using ICEM CFD which is computational grid generating tool and KIVA code to predict the swirl ratio.

Simulated EGR was used to simulate the intake flow in a real engine and flow meters were installed for each of the compressed air, N_2, and CO_2 gases. An air dryer was installed to remove the moisture present in the compressed air. The intake composition was calculated assuming an infinite loop using the fresh air flow rate and fuel injection amount. The calculation formulas are shown below.

O_2 Residual

$$Z = A*y + B*k \quad (1)$$

$$Z = A*y + \frac{x}{1-x}*A*k \quad (2)$$

$$Z = A*y + \frac{x}{1-x}*A*\left(\frac{Z^1-3.474F}{C}\right) \quad (3)$$

$$Z = A*y + x*(Z-3.474F) \quad (4)$$

$$Z = A*y + \frac{x}{1-x}*A*\frac{1-x}{A}*(Z-3.474F) \quad (5)$$

$$Z = (A*y-3.474*F*x)/(1-x) \quad (6)$$

CO_2 and H_2O Residuals

$$Z = A*y + B*k \quad (7)$$

$$Z = A*y + x*(Z + 3.111F) \quad (8)$$

$$Z = (A*y + 3.111*F*x)/(1-x) \quad (9)$$

$$Z = A*y + x*(Z^1 + 3.111F) \quad (10)$$

A: Fresh air flow (g/stroke)
B: EGR flow (g/stroke)
C: A + B
F: Fuel quantity (g)
x: EGR rate (%)
y: Mass fractions of O_2, H_2O, or CO_2 in the fresh air (%)
k: Mass fractions of O_2, H_2O, or CO_2 in the EGR flow (%)

A 498.75 cc single cylinder DI engine was used and the engine was driven by an AC dynamometer. The detailed specifications of the engine are summarized in Table 1. A separate pump cart was made to exclude the effects of lost power for fuel pressurization and the engine was controlled using NI Compact Rio. The combustion characteristics were measured using a Kistler pressure sensor installed in the glow plug position and the exhaust was measured using a AVL Smoke Meter and Horriba Emission Bench. All data was saved using the NI DAQ board (see Fig. 1).

Table 1
Specifications of the test engine and injector.

Description		Specification
Engine	Type	Single cylinder DI engine
	Bore × Stroke (mm)	84 × 90
	Displacement volume (cc)	498.75
	Compression ratio	16
	Valve type	DOHC 4
Injector	Number of injector holes	8
	Direct injection (DI) system	Common-rail
	Nozzle hole diameter (mm)	0.117
	Hydraulic flow rate (cc at 100 bar, 30 s)	350

In order to investigate the effect of swirl and the injector hole number on the light-duty diesel engine, experiments were carried out under the conditions of IMEP 6 bar, which is the low load, and IMEP 10 bar, which is the high load, as shown in Table 2. Conventional conditions were used for each experiment where the conditions for each case are shown in Table 2. In order to investigate the effect of the swirl intensity, a swirl control valve (SCV) was used and the SCV swing experiment was performed at 10° intervals from 0° to 90°. In addition to the conventional injector, 8, 7, 9 and 10 hole injectors were used to study the effects of the injector hole number.

3. Numerical models

In this study, the numerical analysis was carried out using modified KIVA-3V release 2 code coupled with CHEMKIN chemistry [31]. The KIVA-3V code calculates the in-cylinder flow, spray behavior, turbulent flow, pressure, and temperature of each computational cell. The CHEMKIN chemistry solver solves the chemical reactions in the computational cells and calculates the change of the species' mole fractions and internal energies. To predict the ignition and combustion phenomenon, the CHEMKIN chemistry solver was used and the reduced normal heptane mechanism was applied for computational cost efficiency. Patel et al. [32] developed a reduced chemical reaction mechanism of normal heptane from an existing n-heptane mechanism to simulate diesel fuel chemistry. It consisted of 29 species and 52 reactions and agreed well with the experiment results. In this paper, to predict the swirl ratio according to the swirl valve position, a computational 360° full mesh was generated, including the intake, exhaust valve and port, and swirl control valve from 0° (opening) to 90° (closing) in 10° intervals, as shown in Fig. 2. Calculating the swirl ratio using a full mesh proceeded from the intake valve opening (IVO) to the exhaust valve opening (EVO) timing. When calculating the ignition and combustion process, for cost and time efficiency, a sector computational mesh was used instead of a full mesh, as shown in Fig. 3, and the simulation proceeded from the intake valve closing (IVC) timing to EVO timing.

In order to predict the high-pressure direct diesel injection spray break-up, the Kelvin Helmholtz (KH)–Rayleigh Taylor (RT) hybrid break-up model was used [33]. The KH break-up model predicts the break-up of larger blobs into smaller child droplets, which is caused by the instability created by the sheer force between ambient air and the spray referred to as primary breakup. Moreover, the KH break-up model predicts the normal velocity of the child droplets. Secondary breakup, called the RT break-up model, is induced by instability at the interface between two different fluids which have a normal acceleration direction.

The amount of hydrocarbon (HC) was calculated as the sum of the