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Comparisons of Predicted and Measured Results on Performance and Emission of Engine Effected by Intake Air Dilution and Supercharging

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An experimental study was conducted on a single cylinder direct injection diesel engine to investigate the effects of diluting intake air with different gases and increasing intake pressure on combustion process and exhaust emissions. The intake O_2 concentration is changed from 15% to 21% by diluting intake air with different gases(CO_2, Ar, N_2), and the intake pressure is changed from one to two bar by a screw compressor. A modified program for calculating heat release rate, is used to study the characteristics of combustion and exhaust emissions in detail. The main results show that the addition of either CO_2 or Ar to the intake air increases the ignition delay. The variations of ignition delay with CO_2 are much larger than those of ignition delay with Ar for the same O_2 concentration. The emission of NOx decreases with the decrease of O_2 concentration and the smoke level is lower with the addition of the CO_2 than with that of Ar. As the intake pressure is increased, the ignition delay is shortened. Furthermore the high intake air pressure enhances the air-fuel mixing and diffusion combustion, and reduces the premixed combustion, so that NOx emission is decreased without increasing smoke emissions. The addition of CO_2 at high intake pressure, drastically reduces NOx emissions and smoke emission simultaneously at a high load condition, and the addition of CO_2 reduces NOx emissions without affecting the smoke emissions substantially at a low load condition. A zero-dimensional combustion simulation program incorporated with the present heat release correlation and ignition delay correlation is used to predict ignition delay, cylinder pressure and engine power. The results show that the correlations are likely to be adequate for the engine operating under diluted intake air and various intake pressure.

Key Words: Intake Gas Composition, Supercharging, Intake Pressure, Exhaust Gas, Recycling.

1. Introduction

The recycling of the exhaust gases has been applied to internal combustion engines for reducing NOx emissions(EGR) or allowing the engine to operate in the nonair environment (underwater) where air is not freely available. To reduce NOx emissions, a percentage of the exhaust gases which varies between 0 ~ 50% is recycled to the intake system to dilute the fresh mixture.

A number of papers have been published on various aspects of EGR which include diluting intake air with inert gases, and this has helped us gain a better knowledge of the emission formation mechanisms and engine performances as EGR is used(Arcoumanis, 1995 and Yu, 1981). For the recycling engine, it is charged with the mixture of pure oxygen and exhaust gases, instead of air (Asada & Nagai, 1980 and Hawley & Reader,

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1994). Unfortunately, the recycling diesel engine system has some problems which are nonexistent to the operation of diesel engine at the atmosphere environment. For example, the concentration of carbon dioxide in exhaust gases has to be limited to a certain degree to make the engine operate normally. Therefore, to find a effective way of separating carbon dioxide from exhaust gases is very important. It was reported that the highly charging pressure in recycling system was very beneficial for separating process of carbon dioxide. This requires us to investigate the combustion characteristics of diesel engine at a highly charging pressure.

The purpose of this study is to explore the combined effect of intake composition and intake supercharging by increasing intake pressure up to 200kPa and diluting intake air with nitrogen, argon and carbon dioxide. This paper also summarizes the simulation model assumptions and presents the modified heat release correlation and ignition delay correlation for oxygen-diluted diesel engine.

2. Model Description

Zero-dimensional model based on the first law of thermodynamics is used to describe the behavior of mixture contained in a cylinder.

$$\frac{d}{dt}(mu) = -p\frac{dv}{dt} + \frac{dq_w}{dt} + \sum h_j \frac{dm_j}{dt} + H_u \frac{dm_f}{dt} \quad (1)$$

where m is the contained in the cylinder; u is the specific internal energy of the mixture; q_w is the instantaneous heat transfer loss into the cylinder through the chamber walls; $\sum h_i \frac{dm_j}{dt}$ represents the enthalpy fluxes through the intake and exhaust valves; m_f is the fuel mass burned; Hu is the lower heating value of fuel; and p and v represent the cylinder pressure and volume respectively.

For simulating the engine performance under various oxygen contents, significant errors will occur if these heat release rate models are to be implemented in an engine simulation program. Therefore, Assanis et al. proposed a heat release correlation for oxygen-enriched diesel combustion (Zeng & Reader, 1995) as followed:

$$\frac{dm_f}{d\theta} = \theta^{B_p}\exp(A_p - c_p\sqrt{\theta}) + \theta^{B_d}\exp(A_d - c_d\sqrt{\theta}) \quad (2)$$

where θ is the crank angle after ignition, A, B, C and D are adjustable parameters and subscripts p and d correspond to the premixed and diffusion phases, respectively.

Equation (2) is used in this simulation program. The adjustable parameters are modified in terms of the experimental data obtained on a single cylinder direct injection diesel engine.

Ignition delay is calculated from a modified Wolfers correlation (Hawley and Reader, 1994).

The effect of oxygen concentration on ignition delay is taken into consideration by multiplying a term $\left(\frac{O_{2\mathrm{ref}}}{O_2}\right)^2$.

$$\tau_i = A\exp\left(465\frac{0}{T}\right)\left(\frac{1}{p}\right)^{1.19}\left(\frac{O_{2\mathrm{ref}}}{O_2}\right)^n \quad (3)$$

where $O_{2\mathrm{ref}}$ is the reference oxygen concentration corresponding to 21%. A and n are adjustable parameters which are determined according to the experimental data.

3. Experimental Setup

A single cylinder, four stroke, direct injection diesel engine is used in this experiment. Details of the engine specifications are given in Table 1 and the engine test setup is shown in Fig. 1.

A screw compressor is utilized to boost intake pressure up to about 100kPa gauge pressure. The screw compressor is driven by an electric motor. Details of the screw compressor specifications are

Table 1 Engine specifications.

Engine Type	Water cooled D.I. Diesel
Bore × Stroke	95 mm × 95 mm
Compression Ratio	18
Fuel Injection Pressure	23.0 MPa
Injection Nozzle	4 × 0.28 mm

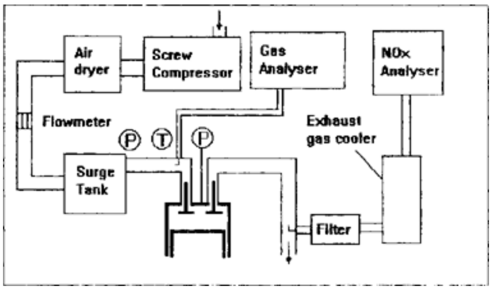


Fig. 1 Schematics of engine test setup.

Table 2 Specification of screw type compressor.

Model		YES 20 GA/GW
Flow Rate		2.44m³/min (2.9kg/min)
Out-let Pressure		Max 6bar(abs)
Motor	HP	20HP
	Volt	220V
	Type	Vertical/STAR-DELTA
Size		$1.2\times1.1\times1.25$ m^3
Weight		420kg
Out-let Diameter		1-1/2 in

given in Table 2. A air dryer is applied to keep the compressed air temperature at 300K to avoid the effect of the intake temperature on combustion and emission characteristics. A gas sampling tube located in the intake manifold induces the intake air to a gas analyzer which is used to measure and control the intake oxygen concentration of the air entering the engine. The intake air is diluted with nitrogen, argon and carbon dioxide respectively. The cylinder pressure diagrams are measured by using a 486 PC computer coupled with a universal data acquisition system, a Kistler pressure sensor and a charge amplifier.

4. Test Conditions

To maintain the permissible maximum cylinder pressure, the compression ratio of the original engine must be decreased to 13.2 because the intake pressure is boosted up to 2.0 bar. Oxygen concentration of intake air is varied from 21% to 16% by volume by adding nitrogen and argon

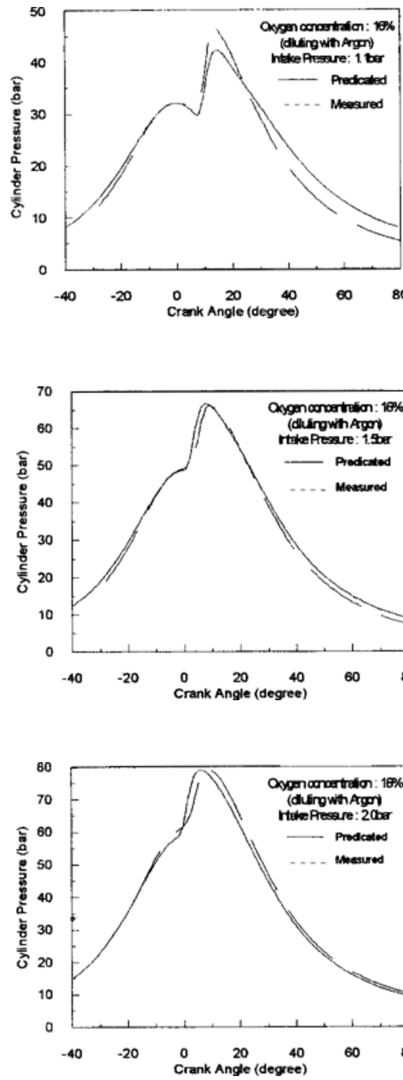


Fig. 2 Comparison of predicted and measured cylinder pressure under various conditions.

respectively. In case of adding carbon dioxide, oxygen concentration can only be varied from 21% to 19% by volume. This is because the addition of carbon dioxide has a great effect on ignition delay. When oxygen concentration is lower than 19%, the engine is not able to operate. For the given oxygen concentration and intake pressure, cylinder pressure data are recorded at a engine speed of 1800rpm and a fuel delivery of 30.2mg/cycle. In this case, the load of engine is varied by the quantity of inert gas which is inserted in the cylinder. And the rpm and fuel consumption are constant. Because the fuel consumption is very important in the recycle system, we fixed the fuel consumption and let the load variable.

5. Results and Discussions

5.1 Comparison of predicted and measured results

5.1.1 Cylinder pressure

Figure 2 shows the measured and predicted cylinder pressure at various intake pressures when the engine is charged with pure air and, air diluted with argon and nitrogen. It can be seen that there is a good agreement between the measured and predicted data when the intake pressure is 1.5bar and 2.0bar. Whereas the predicted cylinder peak pressure is lower than the measured one when the intake pressure is 1.1bar. In this case, long ignition delay leads to combustion start after top dead center due to lower intake pressure. This seems not to occur in real engine operating conditions.

5.1.2 Engine power

Figure 3 shows the comparison between the measured and predicted engine brake power. The predicted engine power closely follows the measured data in both magnitude and trend at different intake pressures and intake compositions.

The above comparisons between predicted and measured data indicate that the heat release rate correlation and ignition delay correlation proposed in this paper are appropriate for estimating the effects of oxygen concentration on ignition delay and combustion under different

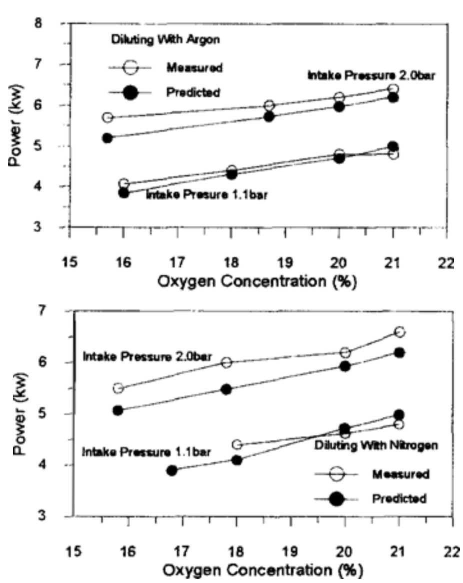
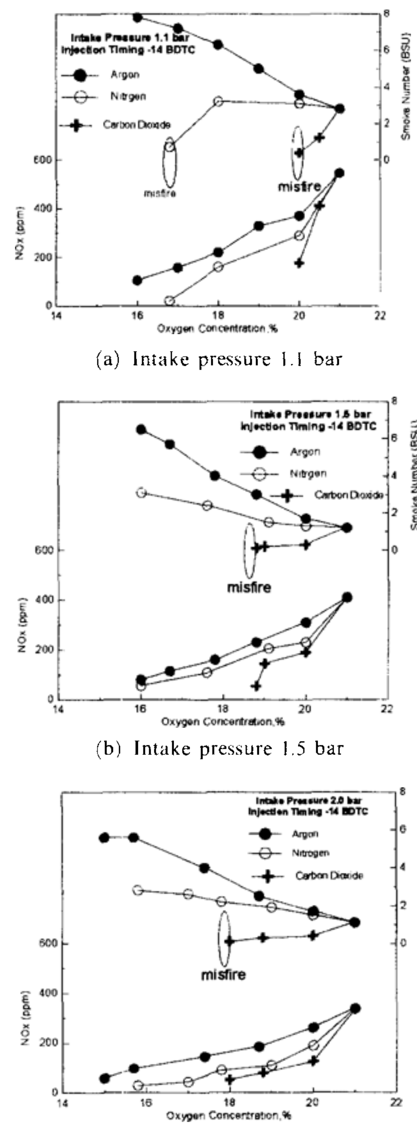


Fig. 3 Comparison of predicted and measured engine power.



(a) Intake pressure 1.1 bar

(b) Intake pressure 1.5 bar

(c) Intake pressure 2.0 bar

Fig. 4 Effects of Intake air composition on emissions.

intake pressure while the intake air is diluted with argon and nitrogen.

5.2 Emission characteristics

Figure 4 shows the smoke and NOx emission characteristics when intake air is diluted with argon, nitrogen and carbon dioxide at the intake pressures of 110kPa, 150kPa, and 200kPa. This figure indicates that, firstly, reductions in NOx emissions are almost in proportion to the decrease in oxygen concentration of intake gases and the increase in intake pressure, secondly, reduction in oxygen concentration is very effective in reducing NOx emissions at relatively lower intake pressures, and third, the effects of addition of inert gases as diluents on reducing NOx are, in order, quantitatively, carbon dioxide, nitrogen and argon. It is also clear from this figure that the smoke emission level is increased by the reduction in oxygen concentration with both argon dilution

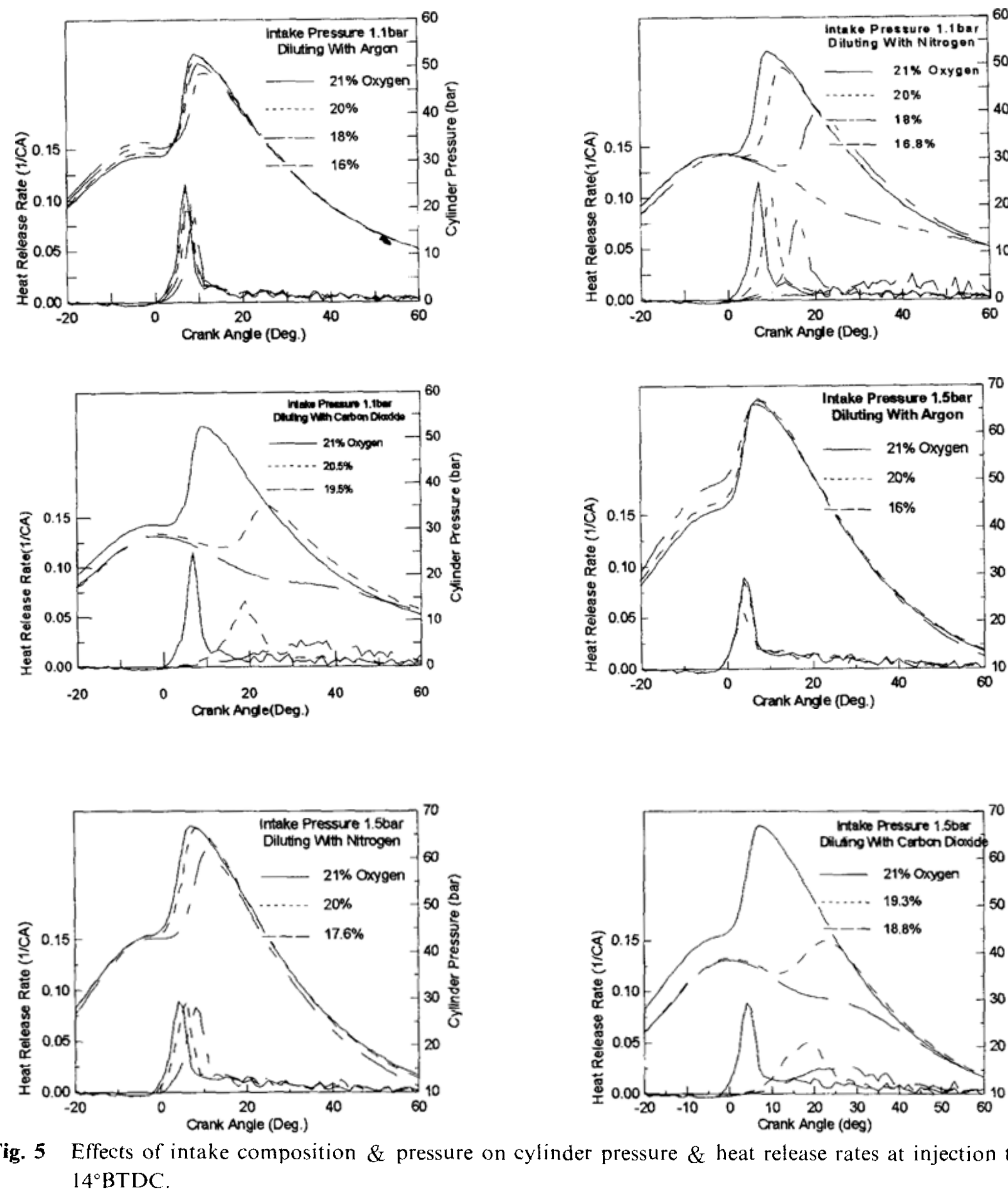


Fig. 5 Effects of intake composition & pressure on cylinder pressure & heat release rates at injection timing 14°BTDC.

and nitrogen dilution at every specific intake pressures, especially for the case of argon dilution. However, the smoke emission level is substantially reduced by the addition of carbon dioxide as a diluent. The same results were reported by Unhida(1993).

5.3 Combustion characteristics

Figure 5 shows the cylinder pressure and heat release rate histories for diluting intake air with argon, nitrogen, and carbon dioxide at intake pressures of 110kPa and 150kPa. For all the cases, cylinder charge pressure during compression stroke is slightly decreased by the addition of carbon dioxide and nitrogen due to the higher specific heat of both diluents, while the cylinder charge pressure during compression stroke is increased by the addition of argon due to its lower specific heat. This could primarily affect combustion and emission characteristics.

When the intake pressure is 110kPa (Fig. 5), the initial heat release rate and cylinder peak pressure are reduced with the decrease of oxygen concentration. The effect of oxygen concentration on ignition delay at different intake pressure is shown in Fig. 6. Clearly, the decreased oxygen concentration leads to the increased ignition delay, and the increased intake pressure can

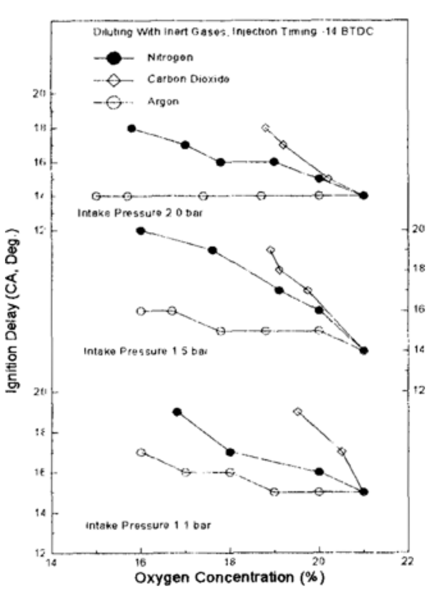


Fig. 6 Effects of intake air composition and pressure on ignition delay.

reduce the ignition delay. The longest and shortest ignition delays are observed by diluting intake air with carbon dioxide and argon respectively.

When the intake pressure is boosted to 150kPa (Fig. 5), the cylinder peak pressure is decreased by diluting intake air with nitrogen and carbon dioxide while are slightly affected by the addition of argon. This could be due to overall effect of two factors: the increased intake pressure leads to reduction in ignition delay and the oxygen concentration decreased by adding argon leads to increase in ignition delay. In this case, we make the temperature constant using the intercooler which is installed in a screw compressor and use the air dryer to eliminate water. The outlet temperature of compressor is approximately 15°C.

Consequently, the ignition delay is maintained almost constant when the intake air is diluted with argon as shown in Fig. 6.In the study on the diesel engine EGR conducted by some researchers previously, the effect of EGR on reduction in NOx was explained as the increased ignition delay, increased heat capacity of the intake charge, and decreased oxygen concentration. Interestingly, NOx emissions are still decreased with oxygen concentration in case of argon dilution although the ignition delay are constant. Evidently, there is no direct connection between the increased ignition delay and decreased NOx emissions. Therefore, the increased ignition delay is not a main reason for effect of EGR on NOx. On the other hand, although the heat capacity of the intake charge is decreased in case of diluting intake air with argon because of lower specific heat of argon than that of air, NOx emissions are not increased but decreased. This result does not support the explanation that the increased heat capacity of the intake charge is a main reason for effect of EGR on NOx emissions. Therefore, the reduction in NOx emissions should be due to the decreased oxygen concentration of intake charge resulting from diluting intake air with inert gases.

The premixed combustion reduces substantially with the addition of argon is observed in Fig. 6. The reduction in premixed combustion leads to form much of the fuel rich areas suitable to soot formation during the diffusion combustion. This, probably, is the reason of increase in smoke emissions when the intake air is diluted with argon. This idea is also supported by the fact that the addition of carbon dioxide as a diluent substantially reduces the smoke emissions. In this case, the increase in premixed combustion due to longer ignition delay lessens the fuel rich areas required for soot formation and the longer ignition delay retards the formation of soot (Heywood, 1988).

Finally, it can be known that the partial misfire occurs in the case that carbon dioxide and nitrogen are added as diluents. The oxygen concentration limited by misfire is reduced as the intake pressure is increased.

6. Summary

An experimental study has been performed to examine the effect of intake composition & intake pressure on combustion and exhaust emission characteristics of a single cylinder direct injection diesel engine. And a computer simulation program has been modified to predict the performance of a DI diesel engine for operating at different intake pressure with various level of oxygen concentration. The results reveal the following:

(1) The addition of inert gases (argon, carbon dioxide and nitrogen) to intake air drastically decreases NOx emissions when the intake pressure is boosted up to 200kPa.

(2) The addition of argon leads to the evident increase in smoke emissions, and the addition of nitrogen leads to the moderate increase in smoke emissions. Contrarily, the addition of carbon dioxide leads to the substantial decrease in smoke emissions.

(3) The reason of increase in smoke emissions is due to the decreased premixed combustion when the intake air is diluted with argon. However, in case of Ar, NOx emission is decreased and the engine performance is comparatively stable even though the quantity of Ar is increased until the concentration of O_2 reach to 16%. If we use the same quantity of the gases (N_2, CO_2), it is impossible to operate the engine stable. Therefore it is reasonable to use the argon as a inert gas in consider of engine performance.

(4) The reduction in smoke emissions, as the addition of carbon dioxide, is due to the increased premixed combustion and decreased fuel burned during the diffusion combustion.

(5) A modified heat release rate correlation and an ignition delay correlation, in which the effect of oxygen concentration in intake air are taken into account, are proposed. The program has been satisfactorily proved with experiment results.

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