

*Full Length Research Paper*

# Use of exhaust gas recirculation (EGR) and cyclonic separator for simultaneous NO<sub>x</sub> and PM reduction in DI diesel engines

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Accepted 10 March, 2011

**This study presents the results of exhaust gas recirculation (EGR) and cyclonic separator for simultaneous oxides of nitrogen (NO<sub>x</sub>) and particulate matter (PM) reduction in a direct injection (DI) diesel engine under different engine loads and speeds. There is a significant NO<sub>x</sub> reduction by EGR, but PM is hugely increased, especially at high EGR rate-high load conditions. A significant reduction in PM is achieved by the use of cyclonic separator without deteriorating other emissions. At high speed-high load conditions, the cyclonic separator has a greater efficiency. Both NO<sub>x</sub> and PM reduce simultaneously when EGR and cyclonic separator are used together. Using cyclonic separator with high EGR rates, a remarkable NO<sub>x</sub> reduction is possible keeping the PM level significantly lower than non-EGR level.**

**Key words:** Exhaust gas recirculation, cyclonic separator, direct injection diesel engine, diesel emissions, oxides of nitrogen and particulate matter.

## INTRODUCTION

Carbon dioxide (CO<sub>2</sub>) is one of the main products of combustion of internal combustion (IC) engine that has a significant share on green house effect as well as on global warming. The emission of CO<sub>2</sub> is directly proportional to the fuel consumption. Fuel consumption and CO<sub>2</sub> emission from DI diesel engines are 20 to 30% less than that of gasoline engines and a reason of increasing DI diesel engine vehicles worldwide. However, higher PM and NO<sub>x</sub> are the main disadvantages. NO<sub>x</sub> is formed in the combustion chamber when nitrogen and oxygen are present in a high temperature region. Strategies used to reduce NO<sub>x</sub> emissions include: injection timing retard, injection rate shaping, charge air chilling, water fuel emulsions, exhaust gas recirculation, etc. Injection timing retard can be used to reduce peak flame temperature and NO<sub>x</sub> emissions, but at the expense of fuel consumption. Injection rate shaping can be used to tailor the injection event to reduce peak flame temperature and NO<sub>x</sub> emissions. Charge air chilling is an effective method of NO<sub>x</sub> control. However, it is not a viable solu-

tion to large brake specific fuel consumption (BSFC) penalty and the increase in cost and package size. Water fuel emulsions are another technology used to reduce NO<sub>x</sub> emissions. However, the water emulsion system must have the ability to control the water content in the fuel as a function of engine speed and load. EGR is now the most popular technology to reduce NO<sub>x</sub>. This study investigated EGR to reduce NO<sub>x</sub>. A well-developed EGR system can significantly reduce engine NO<sub>x</sub> by diluting the fuel air mixture with inert mass. Many engines produced after the 1973 model year has an EGR valve between the exhaust and intake manifolds. The valve opens under certain conditions to admit exhaust into the intake tract. Exhaust gas has a higher specific heat than air, and so it serves to lower peak combustion temperatures. This, in turn, reduces the formation of NO<sub>x</sub>. Ladommatos et al. (1998), Schubiger et al. (2001), Jacobs et al. (2003), Maiboom et al. (2008) and Wenzel et al. (2006) have reported a significant amount of NO<sub>x</sub> reduction in diesel engines by the use of EGR.

An investigation was conducted by Ladommatos et al. (1998) on a high speed- direct injection diesel engine and was concerned with the effects of exhaust gas recirculation (EGR) on diesel engine combustion and

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emissions. In particular, the effects on combustion and emissions of carbon dioxide and water vapor ( $H_2O$ ), principal constituents of EGR, were analyzed and quantified experimentally. It was found that when  $CO_2$  or  $H_2O$  displaced  $O_2$  in the inlet charge, both the chemical and thermal effects on exhaust emissions were small. However, the dilution effect was substantial, and resulted in very large reductions in exhaust  $NO_x$  at the expense of higher PM emissions. Schubiger et al. (2001) focused on the effects of EGR in combination with very high injection pressure.

The  $NO_x$  emissions decreased almost linearly with the EGR; extremely low  $NO_x$  emissions levels (less than 1 to 2 g/kWh) can be achieved at EGR rates up to 40%. A strong increase in the PM emissions was measured with high rates of EGR, but the effect can be significantly counteracted in a certain range by using very high injection pressures up to 160 MPa. Jacobs et al. (2003) studied the complex interactions resulting from the application and control of EGR on a production heavy duty diesel engine system, and its effectiveness in reducing  $NO_x$  emissions. It was shown that EGR provides an effective means for reducing flame temperatures and  $NO_x$  emissions, particularly under low air to fuel (A/F) ratio conditions.

However, engine thermal efficiency tends to decrease with EGR as a result of decreasing indicated work and increasing pumping work. An experimental study was conducted by Maiboom et al. (2008) on a 2.0 l HSDI automotive diesel engine under low load and part load conditions in order to distinguish and quantify some effects of EGR on combustion and  $NO_x$ /PM emissions. At low load conditions, use of high EGR rates at constant boost pressure is a way to drastically reduce  $NO_x$  and PM emissions but with an increase in BSFC and other emissions (CO and hydrocarbon), whereas EGR at constant air/fuel ratio may drastically reduce  $NO_x$  emissions without important penalty on BSFC and soot emissions but is limited by the turbocharging system. Wenzel et al. (2006) studied the effect of EGR and its impact on reducing  $NO_x$  emissions from biodiesel fuel combustion. The application of EGR was found to be an effective method of reducing  $NO_x$  emissions from biodiesel fuel.

The reduction of PM emissions from diesel engines is one of the most challenging problems associated with the exhaust air pollution control. PM emissions can be controlled by the adjustments of the combustion parameters of a diesel engine but these measures result in increased emissions of  $NO_x$ . There are many types of control technologies available to control diesel particulate matter, such as diesel oxidation catalysts (DOC), diesel particulate filters (DPF), fuel additives, alternative diesel fuels, cyclonic separator, etc. DOC reduces the emissions of PM, carbon monoxide (CO) and gaseous reactive organic gas (ROG) from diesel engines by catalytic oxidation. The technology is only effective on the soluble organic fraction of diesel PM, and therefore the overall reduction that can be achieved by a DOC is limited: the

range of reduction is typically between 10 to 30%.

DPF reduces diesel PM emissions through filtration. This technology is very efficient in controlling diesel PM emissions, and has been demonstrated to reduce diesel PM by over 90%. DPF holds out the prospects of substantially reducing regulated particulate emissions but the question of the reliable regeneration of filters still remains a difficult hurdle. Many of the solutions proposed to date suffer from high engineering complexity, cost, thermal cracking, increased backpressure which in turn deteriorates diesel engine combustion performance. Fuel additives are essentially any substances added to the fuel. These additives can reduce the total mass of PM, with variable effects on CO,  $NO_x$  and ROG production. Fuel borne catalysts (FBC) are additives to diesel fuel to aid in soot removal in DPFs by lowering the ignition temperatures of the carbonaceous particles in the exhaust stream.

An alternative diesel fuel is a fuel that can be used in a diesel engine without modification to the engine. Alternative diesel fuels include emulsified fuels, biodiesels, Fischer-Tropsch (F-T) fuels and any combination of these fuels with regular diesel fuels. A fuel-water emulsion creates a leaner fuel to air ratio in the combustion chamber, generating less soot at combustion, thus lowering PM emissions. Biodiesel is a mono-alkyl ester-based oxygenated fuel made from vegetable oils, such as oilseed plants or used vegetable oils, or animal fats. U.S. EPA evaluated biodiesel using publicly available data and concluded that while biodiesel and biodiesel blends reduce PM, ROG, and CO emission,  $NO_x$  emissions increase. However, biodiesel usually costs higher than the cost of conventional diesel. Fischer-Tropsch fuels have been used to some degree since the 1920s. Today, these fuels are being used in South Africa to power buses, trucks and taxicabs. Fischer-Tropsch fuels have emissions reduction benefits including PM emissions. A cyclonic separator is a dust collector and this device can also be successfully used to separate PM from diesel exhaust reported by Grade et al. (1989), Mukhopadhyay et al. (2006), Crane and Wisby (2000), Akhter and Nabi (2005) and Roy and Hoque (2007). Grade et al. (1989) presented an experimental investigation on particulate control of diesel engine exhaust using a low cost cyclonic separator.

A significant amount of PM reduction was reported. Mukhopadhyay et al. (2006) presented an improved computer aided analytical approach for controlling diesel soot particulate emission by cyclone separator. Reduction of soot particles in the exhaust in turn reduces the diesel particulate matter formation. Cyclone separator with low initial cost, no thermal failure, and simple construction produces low back pressure and reasonably high particulate collection efficiencies with reduced regeneration problems. A particulate after-treatment system has been developed by Crane and Wisby (2000) and applied to a 2.5 l direct-injection diesel engine. The base exhaust system configuration included an oxidation

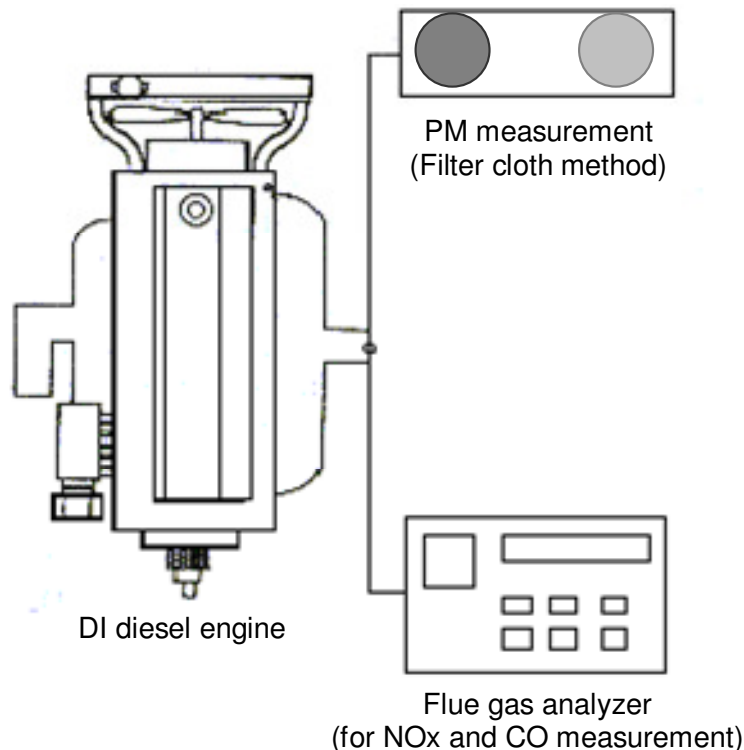


Figure 1. Schematic diagram of the experimental system.

catalyst; to this has been added a compact heat exchanger believed to have the potential for promoting particle growth, followed by four inclined reverse-flow cyclones in parallel. Emission measurements have shown that the system is capable of reducing exhaust particulate mass concentrations by up to 70%. The feasibility of a cyclone-based after-treatment system for production vehicles is also discussed. A simple, low cost, cyclonic separator has been designed, fabricated and tested by Akhter and Nabi (2005) to separate the particulate matter from diesel engine exhaust. It was found that within the range of design/rated rpm, efficiency of the cyclone increases with increase in torque. However the efficiency of the separator was found to decrease as the engine was run at a speed higher than the design speed. As evident from the result, it was possible to reduce significant mass of the particulate matter from the diesel exhaust without any change in engine performance and back pressure.

Roy and Hoque (2007) investigated the effect of EGR and a cyclonic separator to reduce NO<sub>x</sub> and PM from engine exhaust. A significant reduction in PM was obtained by the use of cyclonic separator without deteriorating other emissions and fuel consumptions. In that study, one engine speed was attempted. This study is the extension of the previous study. Here, three engine speeds with different engine loadings are considered. This study found that the use of cyclonic separator with EGR can be a viable option to reduce NO<sub>x</sub> and PM simultaneously in DI diesel engines.

## EXPERIMENTAL SETUP AND TEST PROCEDURE

Figure 1 shows the schematic diagram of the experimental system. The engine used in this study was a Peter diesel engine. It is a four-stroke single cylinder naturally aspirated DI diesel engine with specifications as in Table 1. All experimental data were taken after 30 min of engine start after which the exhaust line temperature became constant and there was almost no fluctuation of emissions. This condition of the engine was chosen because of the consistent data at this condition. Tests were carried out at the warmed up condition of the engine under three engine speeds. The engine speeds were 650 rpm, the lowest speed of the engine, 1200 rpm, the best torque speed of the engine, and 1050 rpm, an intermediate speed of the engine. The lower calorific value of diesel fuel used in this study was 43,000 kJ/kg with cetane number of 50. Stop watch and fuel level indicator were used to measure the fuel consumption rate. Intake air flow rate was measured by an orifice meter, measuring the pressure drop through an inclined manometer. Loads were measured by electric motor/generator dynamometer. The formula used for brake power calculation is:

$$P \text{ (kW)} = 2\pi N \text{ (rev/s)} T \text{ (N.m)} \times 10^{-3};$$

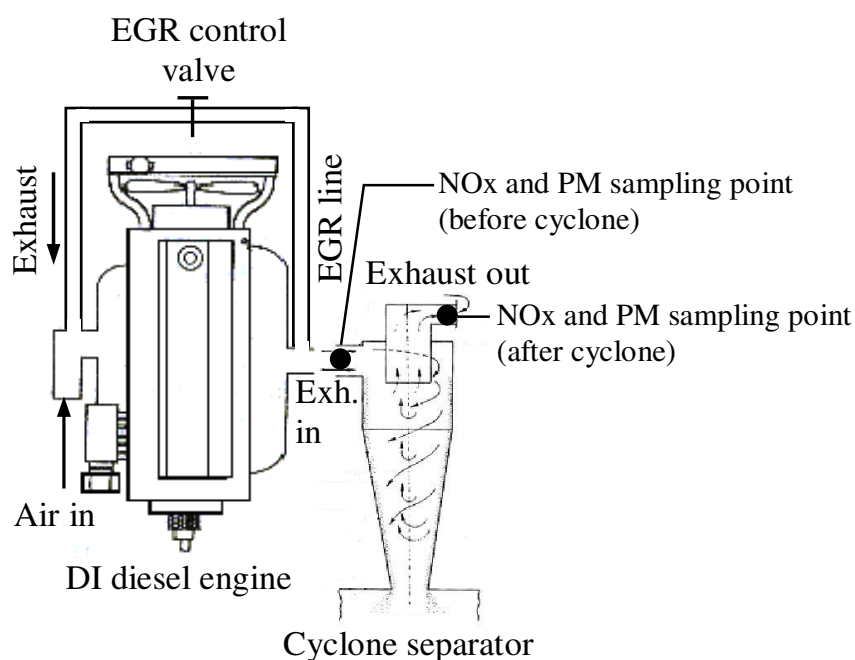
Where N is engine speed in rev/s and T is torque in N.m.

Corresponding to each data point, exhaust emissions were measured.

A flue gas analyzer (IMR 1400) was used to measure the NO<sub>x</sub> and CO of exhaust gases. PM is measured by filter cloth method. Two-stage filtration is used to better separate the PM from exhaust. Two filters are weighed before setting to the exhaust. Then these are set to the exhaust and full flow of exhaust is passed through the filters. Again the filters are weighed with PM loading. Difference of the two

**Table 1.** Engine specifications.

Engine type	4-stroke DI diesel engine
Number of cylinders	One
Bore × Stroke	80 × 110 mm
Swept volume	553 cc
Compression ratio	16.5:1
Rated power	4.476 kW @ 1800 r/min
Fuel injection pressure	14 MPa (900 to 1099 r/min) 20 MPa (1100 to 2000 r/min)
Fuel injection timing	24° BTDC

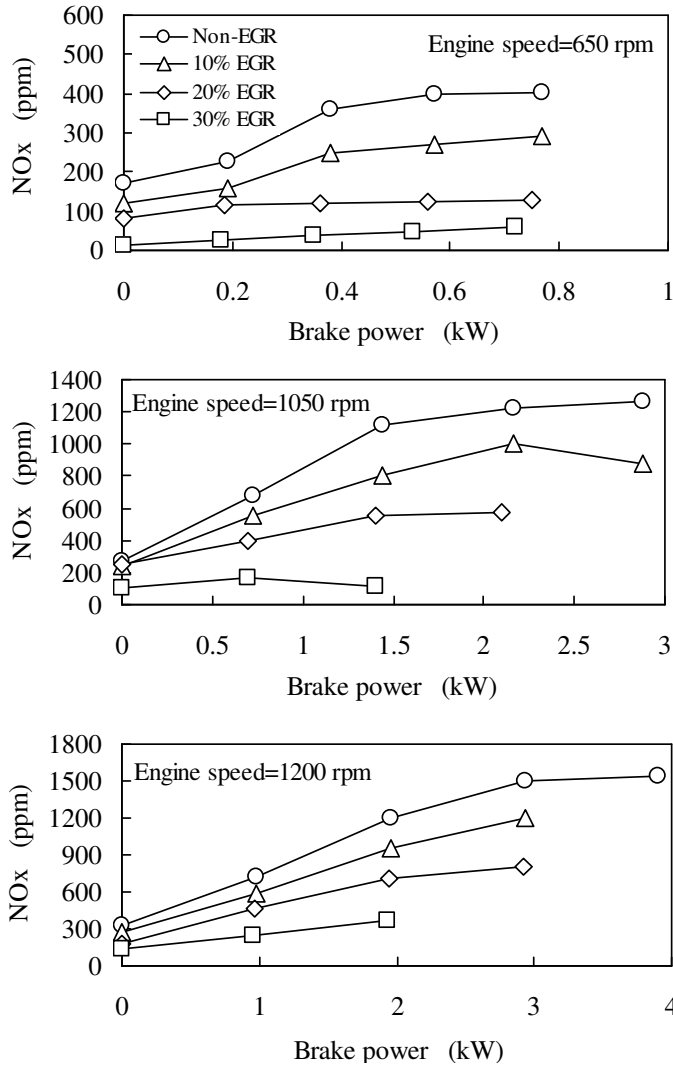
**Figure 2.** Arrangement of EGR and cyclonic separator.

readings before and after their use indicates the PM in the exhaust at that condition. The filters were dried for at least one hour at 105°C before and after each type of sampling to achieve mass consistency and were weighed afterwards with a balance with  $\pm 0.1$  mg accuracy. No significant increase in backpressure is developed during PM collection. Backpressure is measured by a U-tube mercury/water manometer. Figure 2 shows the arrangement of EGR and cyclonic separator. There are two main types of EGR. One is cold EGR where the re-circulated gas is cooled first before mixing with intake air. This favors to lower the combustion temperature more. However, the cold EGR has an unfavorable effect on aldehyde production in the low temperature combustion condition. Moreover, cold EGR needs some cooling system to cool the exhaust, which is costly. Therefore, the cold EGR is not used in this study. The other is hot EGR where the recirculated gas is mixed with intake air without cooling. A hot EGR system is used in this study. For this purpose, a connecting line is made from the exhaust manifold to the air inlet position. The EGR flow was controlled manually by a valve and the EGR level was determined

as the percentage reduction in mass flow rate of air. The following is the equation of EGR calculation.

$$\% \text{ EGR} = (\text{Mass of recirculated gas} / \text{Total mass}) \times 100 = ((\text{Mass of air without EGR} - \text{Mass of air with EGR}) / \text{Mass of air without EGR}) \times 100.$$

The cyclonic separator used in this study is a simple single cyclone. Construction detail was presented by Roy and Hoque (2007) in a previous conference paper. PM-laden diesel exhaust enters a cylindrical chamber tangentially and leaves through a central opening. The PM by virtue of their inertia tends to move toward the separator wall from which they are led into a receiver. Centrifugal force of sufficient strength is obtained by rotational movement. The cyclonic separator was fitted to the exhaust line of the engine and emission test was carried out operating the engine at variable speeds and loads. This cyclonic separator has been designed following the one presented by Grade et al. (1989). Based on test engine configurations



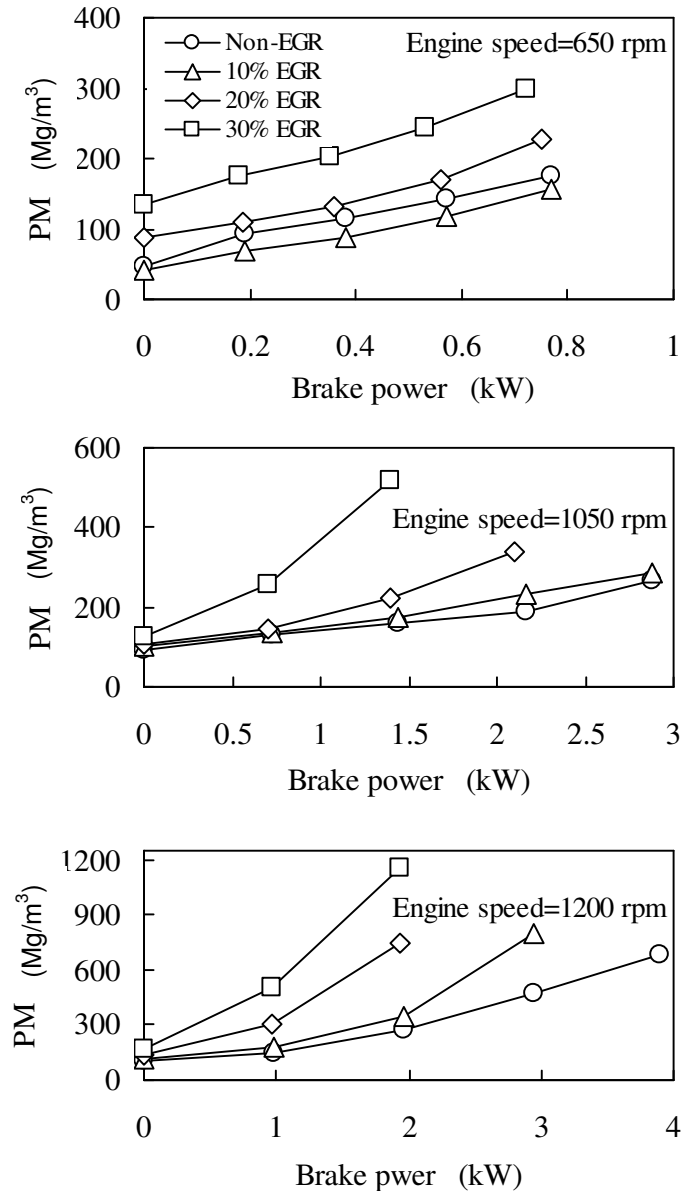
**Figure 3.** NOx emissions without and with EGR at different engine speeds and loads.

and exhaust pipe diameter, inlet diameter of the cyclonic separator has been chosen as 37 mm. Cyclones can be constructed of a variety of types of materials. Mild steel sheet has been used for construction of the present cyclonic separator.

**EXPERIMENTAL RESULTS AND DISCUSSION**

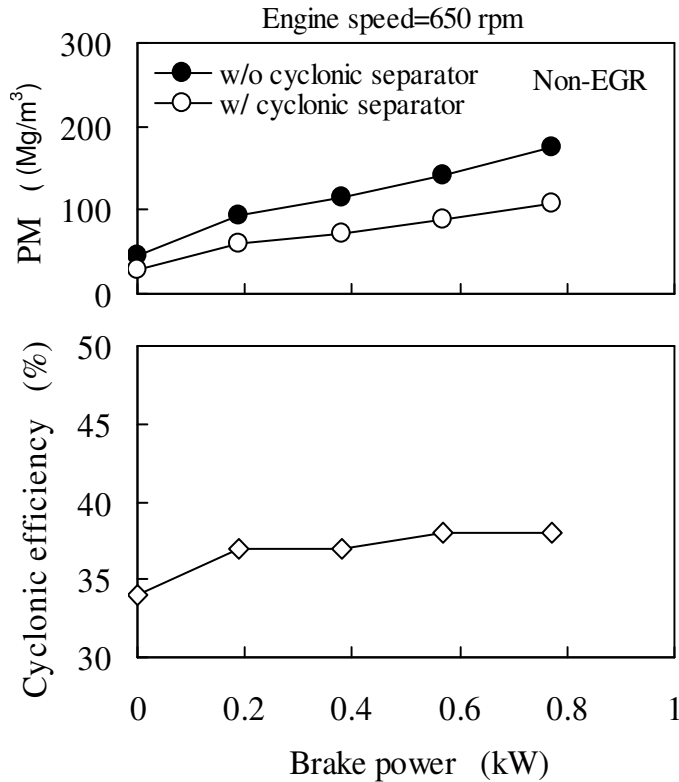
**EGR results**

Figure 3 shows NOx emissions at different engine speeds and loads without and with different EGR rates. At 650 rpm, NOx emission without EGR is 170 ppm at no-load, and increased to 405 ppm at full load; with 10% EGR rate it is 120 ppm at no-load, and increased to 290 ppm at full load; with 20% EGR rate it is increased from 80 ppm at no-load to 130 ppm at full load; and with 30% EGR rate it is increased from only 15 ppm at no-load to 60 ppm at full load. NOx reduction is 30 to 32% at 10% EGR rate,



**Figure 4.** PM emissions without and with EGR at different engine speeds and loads.

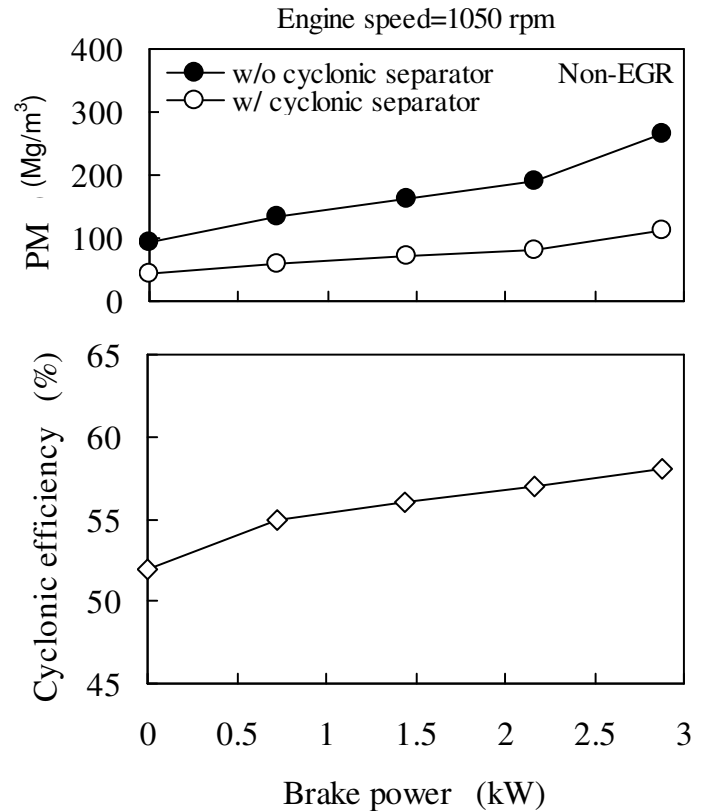
47 to 69% at 20% EGR rate and 85 to 91% at 30% EGR rate depending on engine loads. At 1050 rpm, NOx emission without EGR is 275 ppm at no-load, and increased to 1264 ppm at full load. NOx reduction is 13 to 30% at 10% EGR rate, 10 to 55% at 20% EGR rate and 62 to 90% at 30% EGR rate. Average NOx reductions at 10, 20 and 30% EGR rates under different loads and speeds are about 24, 47 and 77%, respectively than non-EGR. Figure 4 shows PM emission at different engine loads and speeds without and with EGR. PM increased with



**Figure 5.** Cyclonic efficiency at 650 rpm at non-EGR condition at different loads.

increasing engine load and speed. At 650 rpm, at no-load condition without EGR, the PM emission is about 45 mg/m<sup>3</sup>. However, PM emission is increased to 176 mg/m<sup>3</sup> at full load. PM decreased 6.5 to 20% at 10% EGR rate, and increased 12 to 93% at 20% EGR rate and 73 to 189% at 30% EGR rate depending on engine loads.

PM decreased by changing the mode from non-EGR to 10% EGR and then increased with increase in % EGR at this lowest engine speed. This might be due to better evaporation of fuel particles at 10% EGR rate for higher inlet temperature than non-EGR maintaining proper air-fuel ratio (A/F). At 1050 rpm, at no-load condition without EGR, the PM emission is about 94 mg/m<sup>3</sup>. However, PM emission is increased to 266 mg/m<sup>3</sup> at full load. PM increased 5 to 22% at 10% EGR rate, 11 to 79% at 20% EGR rate and 34 to 222% at 30% EGR rate. At 1200 rpm, at no-load condition without EGR, the PM emission is about 100 mg/m<sup>3</sup>. However, PM emission is increased to 680 mg/m<sup>3</sup> at full load. PM increased 15 to 67% at 10% EGR rate, 40 to 265% at 20% EGR rate and 71 to 325% at 30% EGR rate. Average PM increase at 10, 20 and 30% EGR rates under different loads and speeds are about 12, 65 and 156%, respectively than non-EGR. It seems that high EGR-high loading conditions are very prone to large amount of PM production. With high EGR rates at high loading conditions, average A/F ratio in the

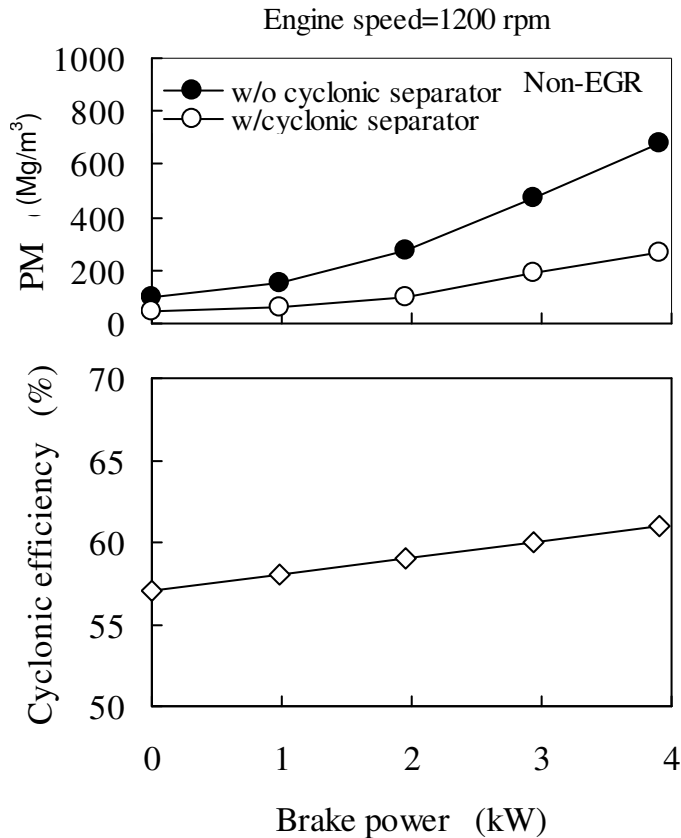


**Figure 6.** Cyclonic efficiency at 1050 rpm at non-EGR condition at different loads.

cylinder tends to become rich making over rich zones in the combustion chamber. Therefore, incomplete combustion of under-mixed fuel/air mixture occurred, and higher PM is produced.

### Cyclonic separator results

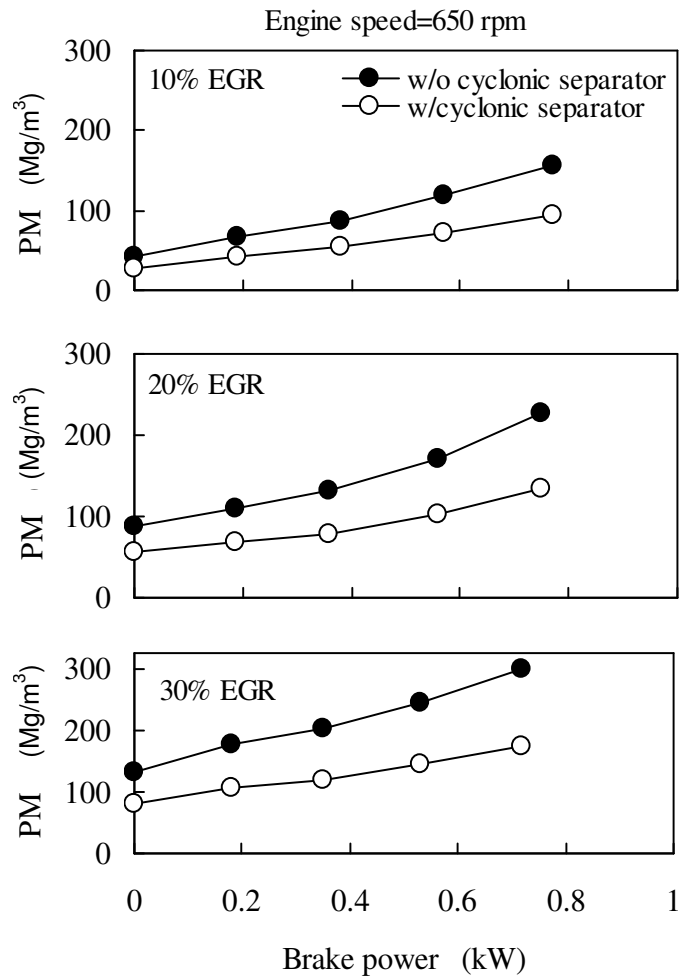
Figure 5 shows PM emissions without and with cyclonic separator under non-EGR condition at 650 rpm, and cyclonic efficiency at different engine loads. PM emission without cyclonic separator is increased from 45 mg/m<sup>3</sup> at no-load to 176 mg/m<sup>3</sup> at full load. The level of PM emission is decreased to 30 mg/m<sup>3</sup> at no-load and 109 mg/m<sup>3</sup> at full load when cyclonic separator is used. The cyclonic efficiency slightly increased from no-load to full load. At no-load condition the efficiency is about 34%, whereas at full load it is about 38%. Figure 6 shows cyclonic efficiency at 1050 rpm at non-EGR condition at different loads. PM emission without cyclonic separator is increased from 94 mg/m<sup>3</sup> at no-load to 266 mg/m<sup>3</sup> at full load. The level of PM emission is decreased to 45 mg/m<sup>3</sup> at no-load and 112 mg/m<sup>3</sup> at full load when cyclonic separator is used. The cyclonic efficiency increased from 52% at no-load to 58% at full load. Figure 7 shows cyclonic efficiency at 1200 rpm at non-EGR condition at



**Figure 7.** Cyclonic efficiency at 1200 rpm at non-EGR condition at different loads

different loads. PM emission without cyclonic separator is increased from 100 mg/m<sup>3</sup> at no-load to 670 mg/m<sup>3</sup> at full load. PM emission decreased to 43 mg/m<sup>3</sup> at no-load and 264 mg/m<sup>3</sup> at full load when cyclonic separator is used. The cyclonic efficiency increased from 57% at no-load to 61% at full load. It is clear from the results that the higher the engine speed, the higher the cyclonic efficiency, and the higher the loads, the higher the cyclonic efficiency too. Average cyclonic efficiency increased with the increase in speeds and loads. Average cyclonic efficiency increased from 37% at 650 rpm to 59% at 1200 rpm. When the engine speed is increased, the exhaust gas speed is also increased.

At higher exhaust speed, higher centrifugal force inside the cyclone is developed, which is favorable for higher PM separation. At higher loading conditions PM production is higher and size is also greater due to agglomeration of soot particles. Greater sized PM has higher centrifugal force that can be separated more easily. This is the reason of higher cyclonic efficiency at higher engine speed and load conditions. Engine backpressure, fuel consumption and emissions of CO were measured at different engine loadings without and with cyclonic separator. There was a slight increase (not significant) in engine backpressure with cyclonic separator. However,

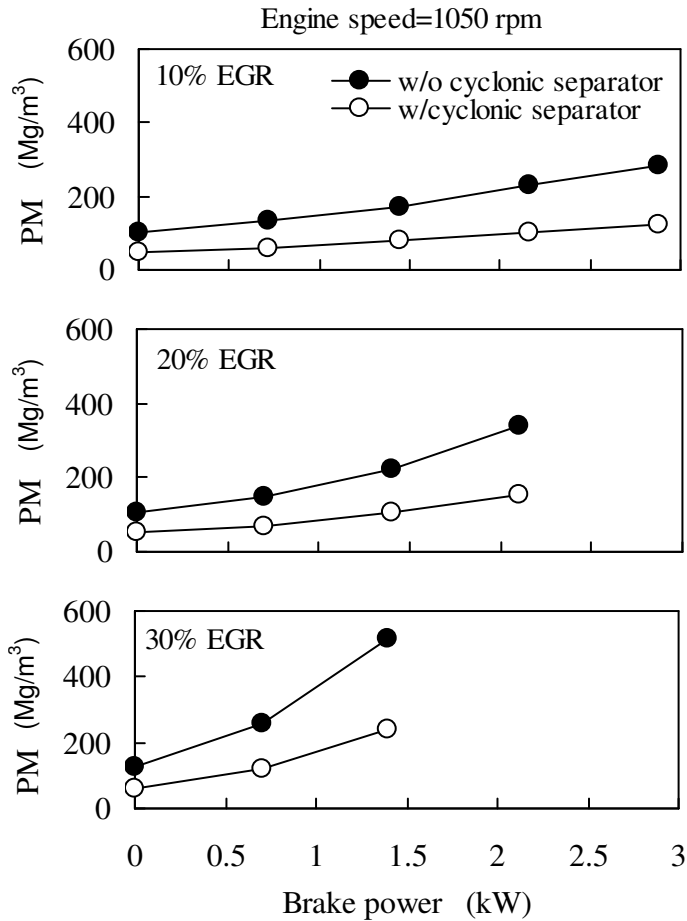


**Figure 8.** PM emissions at 650 rpm without and with cyclonic separators at different loads and EGR rates.

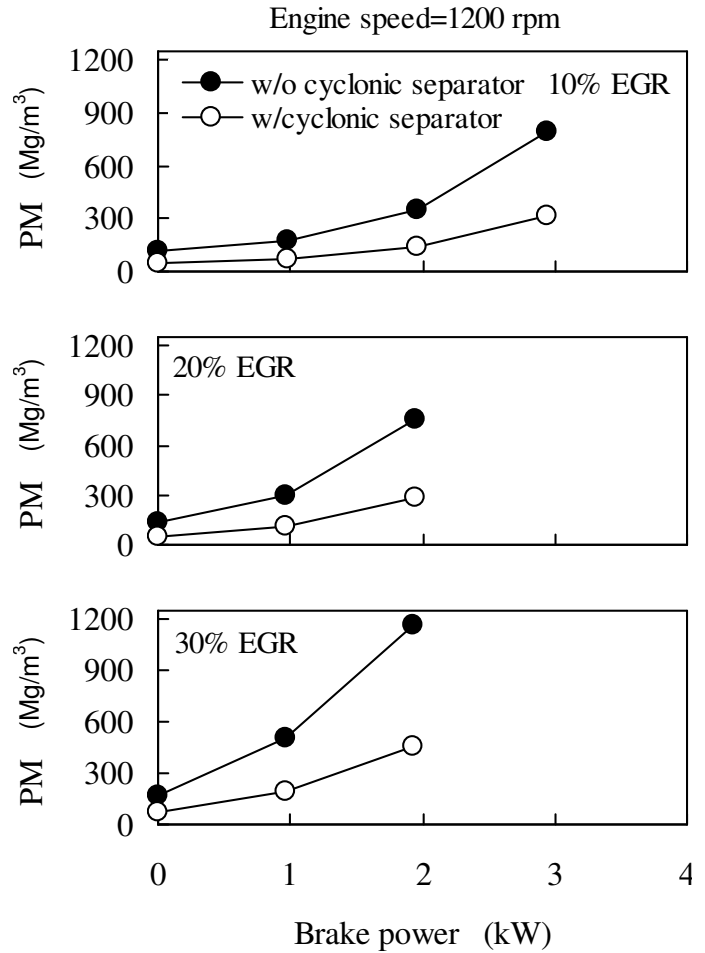
there was no change in fuel consumption and emissions of CO without or with cyclonic separator.

**Combined EGR and separator results**

Figure 8 shows PM emissions at 650 rpm without and with cyclonic separators at different loads and EGR rates. At 10% EGR rate, PM emission at no-load is about 42 mg/m<sup>3</sup>. This increases gradually to 156 mg/m<sup>3</sup> at full load. Cyclonic separator removes PM from exhaust and the level at no-load is about 27 mg/m<sup>3</sup> (36% reduction) and at full load it becomes 95 mg/m<sup>3</sup> (39% reduction). At 20% EGR rate, PM emission at no-load is about 88 mg/m<sup>3</sup> and it becomes 227 mg/m<sup>3</sup> at full load. The level of PM with cyclonic separator at no-load is about 55 mg/m<sup>3</sup> (38% reduction) and at full load it becomes 135 mg/m<sup>3</sup> (41% reduction). At 30% EGR rate, PM emission at no-load is about 133 mg/m<sup>3</sup> and at full load it becomes about 298 mg/m<sup>3</sup>. Cyclonic separator reduces PM from exhaust



**Figure 9.** PM emissions at 1050 rpm without and with cyclonic separators at different loads and EGR rates.



**Figure 10.** PM emissions at 1200 rpm without and with cyclonic separators at different loads and EGR rates

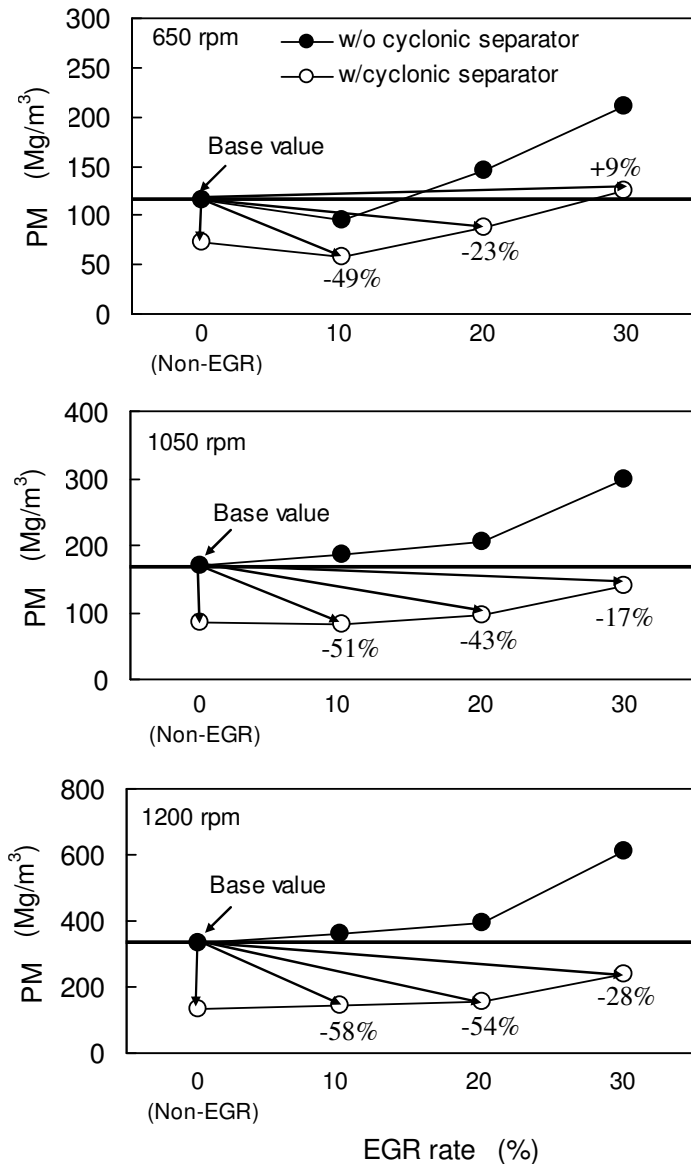
exhaust to the level of 80 mg/m<sup>3</sup> (40% reduction) at no-load and 175 mg/m<sup>3</sup> (41% reduction) at full load. The average PM reduction is about 40%. With increasing EGR rate, there is a slight improvement in cyclonic efficiency. Figure 9 shows PM emissions at 1050 rpm without and with cyclonic separators at different loads and EGR rates. At 10% EGR rate, PM emission at no-load is about 100 mg/m<sup>3</sup>, 138% increase than that of 650 rpm. PM at 10% EGR rate at no-load increased gradually to 284 mg/m<sup>3</sup> at full load which is about 82% increase than that of 650 rpm.

Cyclonic efficiency at no-load was 51% and at full-load, it was 56%. At 20% EGR rate, PM emission at no-load is about 108 mg/m<sup>3</sup> and it becomes 340 mg/m<sup>3</sup> at 2.2 kW brake power (maximum allowable load at this condition). Cyclonic efficiency at no-load is 50% and at maximum load, it is about 55%. At 30% EGR rate, PM emission at no-load is about 126 mg/m<sup>3</sup> and at 1.45 kW brake power (maximum allowable load) it becomes about 519 mg/m<sup>3</sup>. Cyclonic efficiency at no-load and at maximum load is about 54%. The average PM reduction is about 54 to 55% for all EGR rates. Figure 10 shows PM emissions at

1200 rpm without and with cyclonic separators at different loads and EGR rates. At 10% EGR rate, PM emission at no-load is about 115 mg/m<sup>3</sup>. This increases gradually to 794 mg/m<sup>3</sup> at 3 kW brake power (maximum allowable load). Cyclonic efficiency at no-load and at maximum load is about 61%. At 20% EGR rate, PM emission at no-load is about 140 mg/m<sup>3</sup> and it becomes 750 mg/m<sup>3</sup> at 2 kW brake power (maximum allowable load). Cyclonic efficiency at no-load and at maximum load is again about 61%. At 30% EGR rate, PM emission at no-load is about 171 mg/m<sup>3</sup> and at 2 kW brake power (maximum allowable load) it becomes about 1160 mg/m<sup>3</sup>. Cyclonic efficiency at no-load and at maximum load is about 60 to 61%. The average PM reduction is about 61% for all EGR rates. Average cyclonic efficiency with different EGR rates increased from 40% at 650 rpm to 61% at 1200 rpm.

Figure 11 shows average PM reductions with cyclonic separator at different engine speeds and EGR rates than non EGR conditions. At 650 rpm, it shows that average PM emission at non EGR is about 115 mg/m<sup>3</sup>. It increased to 211 mg/m<sup>3</sup> with 30% EGR rate. When





**Figure 11.** Average PM reductions with cyclonic separator at different engine speeds and EGR rates.

cyclonic separator is used, PM emission reduced to 72 mg/m<sup>3</sup> at non EGR and to 125 mg/m<sup>3</sup> at 30% EGR rate. At 10% EGR rate with cyclonic separator, the average PM is 49% less and at 20% EGR rate, the average PM is 23% less than at non EGR. At 30% EGR rate with cyclonic separator, the average PM is only 9% more than non EGR level. At 1050 rpm, average PM emission at non EGR is about 169 mg/m<sup>3</sup>. It increased to 300 mg/m<sup>3</sup> with 30% EGR rate. When cyclonic separator is used, PM emission reduced to 85 mg/m<sup>3</sup> at non EGR and 140 mg/m<sup>3</sup> at 30% EGR rate. At 10% EGR rate with cyclonic separator, the average PM is 51% less and at 20% EGR rate, the average PM is 43% less than at non EGR. Even at 30% EGR rate with cyclonic separator, the average PM is still 17% less than non EGR level. At 1200 rpm,

average PM emission at non EGR is about 335 mg/m<sup>3</sup>. It increased to 610 mg/m<sup>3</sup> with 30% EGR rate. PM emission reduced to 132 mg/m<sup>3</sup> at non EGR and 241 mg/m<sup>3</sup> at 30% EGR rate when cyclonic separator is used. This implies that if EGR and cyclonic separator are used together, NOx is significantly reduced with no increase in PM.

**Conclusions**

This study examined the effect of EGR, a cyclonic separator and their combination on NOx and PM emissions of a DI diesel engine. The following conclusions can be drawn from the experimental results.

1. Average NOx reduction at 10% EGR rate under different loads and speeds is about 24%, but average PM increase is about 12%. NOx is reduced about 47% at 20% EGR rate, but PM increase is about 65%. At 30% EGR rate, NOx reduction is about 77%, but PM increase is about 156%.
2. A simple cyclonic separator reduces PM from diesel exhaust about 34-61% without deteriorating other emissions and fuel consumption. Average cyclonic efficiency increased with the increase in speeds and loads. Average cyclonic efficiency increased from 37% at 650 rpm to 59% at 1200 rpm.
3. Use of EGR and cyclonic separator together can simultaneously reduce NOx and PM from diesel exhaust. Combining the cyclonic separator with 10% EGR rate, average PM reduction than non-EGR is 53% maintaining average NOx reduction of 24%. At 20% EGR rate, average PM reduction than non-EGR is 40% maintaining average NOx reduction of 47%. And at 30% EGR rate, average PM reduction than non-EGR is 12% maintaining average NOx reduction of 77%.

Two recommendations are proposed to address the fuel quality effect and high pressure injection effect, which is our next plan.

- 1) Engine test with biodiesel to see the performance of EGR and cyclonic separator. Biodiesel in diesel engines produces higher NOx and lower PM. EGR is expected to reduce NOx significantly and cyclonic separator can reduce the PM even lower.
- 2) Engine test at higher fuel injection pressures (up to 100 MPa or more) with smaller nozzle hole diameter (dia. as small as 0.1 mm). This condition improves atomization and the inhomogeneity of local air fuel mixture. Therefore, smaller size PM can be expected. Cyclonic separator with high pressure injection system gives the information whether it is effective to control smaller PM in modern diesel engines.

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