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EFFECT OF EGR AND CYCLONIC SEPARATOR ON EMISSIONS IN DI DIESEL ENGINES

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ABSTRACT

This study investigated the effect of EGR on emissions in a DI diesel engine at different engine loading conditions (from no-load to full load). Although the NOx is reduced significantly by EGR, other emissions like CO and PM are excessively increased, especially at high EGR-high loading conditions. Fuel consumption is also increased at high EGR rate. A cyclonic separator has also been tested to reduce the PM from engine exhaust. A significant reduction in PM is obtained by the use of cyclonic separator without deteriorating other emissions and fuel consumptions. At higher loading conditions, the cyclonic separator showed greater efficiency. When EGR and cyclonic separator are used together, both NOx and PM are reduced. Using cyclonic separator with high EGR rate, NOx is reduced 80% or more keeping PM level below to the level of non-EGR.

Keywords: Exhaust gas recirculation, Cyclonic separator, Diesel emissions.

1. INTRODUCTION

Carbon dioxide (CO_2) 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_2 is directly proportional to the fuel consumption. Fuel consumption and CO_2 emission from direct injection (DI) diesel engines are 20-30% less than that of gasoline engines and a reason of increasing DI diesel engine vehicles worldwide. However, higher particulate matters (PM) and oxides of nitrogen (NOx) are the main disadvantages. This study investigated exhaust gas recirculation (EGR), a cyclonic separator, and their combination to observe their emission reduction potential, especially NOx and PM reduction in DI diesel engines.

EGR has a long history in gasoline engines to reduce NOx. A significant amount of NOx reduction in diesel engines by the use of EGR has also been reported [1-3]. EGR can increase the intake air temperature, which may reduce ignition delay, and shorter ignition delay is favorable for lower emissions. However, at low temperature combustion with low oxygen content in the cylinder, there is an increase in PM and CO with EGR. This study carefully examined the effect of EGR on NOx as well as CO and PM emissions at a constant engine speed with various engine loads. EGR rate up to 30% is investigated in this study.

A cyclonic separator is a dust collector and this device can also be successfully used to separate PM from diesel exhaust [4,5]. A simple cyclonic separator is used in this study to reduce the PM from diesel engine exhaust. A significant reduction in PM is obtained by the use of cyclonic separator. There is no change in emissions of other components, and engine backpressure and fuel consumption are unchanged.

When EGR and cyclonic separator are used together, NOx is reduced about 25-85% depending on EGR percentages, while PM is reduced about 50-70%. The most significant result is 80-85% NOx reduction with 30% EGR. However, PM is increased about 1.5 to 11 times in this condition. Using cyclonic separator with 30% EGR, PM is decreased even below to the level of non-EGR condition. This means that the use of cyclonic separator with EGR can be a viable option to reduce NOx and PM simultaneously in DI diesel engines.

2. EXPERIMENTAL SETUP AND TEST PROCEDURE

Figure 1 shows the schematic diagram of the experimental system. A four-stroke single cylinder naturally aspirated stationary DI diesel engine with specifications as in Table 1 was used. All experimental data were taken after 30 minutes of engine start after which the exhaust line temperature is no further increased i.e. constant and there is almost no fluctuation of emissions. This condition of the engine is chosen because of the consistent data at this condition. Tests were carried out at the warmed up condition of the engine with or without EGR at different engine loadings and with or without cyclonic separator. Engine test conditions are shown in Table 2. The diesel fuel used in this study was No. 2 diesel fuel with lower calorific value of 43000 kJ/kg and cetane number 50.

A flue gas analyzer (IMR 1400) was used to measure carbon monoxide (CO) and NOx 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 these 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 readings before and after their use indicates the PM in the exhaust at that condition. No significant increase in backpressure is developed during PM collection. Backpressure is measured by a U-tube mercury/water manometer. Fuel and air consumptions are also measured at different engine conditions.

Figure 2 shows the arrangement of EGR and cyclonic separator. EGR is controlled by an EGR valve. 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 re-circulated 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 (EGR line is shown in Fig. 2). The percentage of EGR was selected by the volume ratio. The following is the equation of EGR calculation.

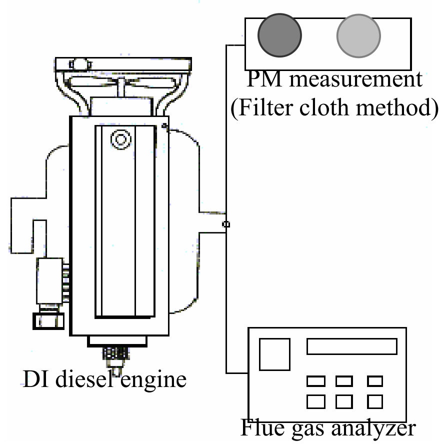

Fig 1:Schematic diagram of the experimental system

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 (900-1099 r/min) 20 MPa (1100-2000 r/min)
Fuel injection timing	24° BTDC

Table 2: Engine test conditions

Non-EGR		
Engine speed (rpm)	Engine load (N)	Engine torque (N-m)
1000	0 (no-load)	0
	19.6 (¼load)	6
	39.2 (½load)	12
	58.8 (¾load)	18
	78.4 (full load)	24
EGR (engine speed 1000 rpm)		
EGR rate	Engine load	Engine torque (N-m)
10%	No-load, ¼ load, ½ load, ¾ load, full load	0, 6, 12, 18, 24
20%	No-load, ¼ load, ½ load, ¾ load	0, 6, 12, 18
30%	No-load, ¼ load, ½ load	0, 6, 12

% EGR = volume of re-circulated gas/total volume

The cyclonic separator used in this study is a simple single cyclone. 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 of a diesel engine and emission test was carried out operating the engine at constant speed with variable engine loads. This cyclonic separator has been designed following the one presented in ref. [4]. The detail of design and construction has been presented [5]. Based on test engine configurations 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. Various dimensions of the cyclonic separator have been shown in Fig. 3, where Fig. 3(a), 3(b) and 3(c) represent correspondingly front view, side view and top view of the separator. The various dimensions and the material selected enable the cyclonic separator to be a light and compact one that can be used in DI diesel engine vehicles. The efficiency of the cyclonic separator was calculated by the ratio of the weight of particles trapped in the cyclonic separator to the weight of the particles without using the cyclonic separator

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 EGR Results

Figure 4 shows NOx emission at different engine loading conditions (from no-load to full load) without and with different EGR rates. It is to be noted that non-EGR and 10% EGR can tolerate up to full load. However, 20% EGR tolerates up to ¾ loads, while 30% EGR allows only up to ½ loads. With higher EGR rates at high loading conditions, average air-fuel ratio (A/F) in

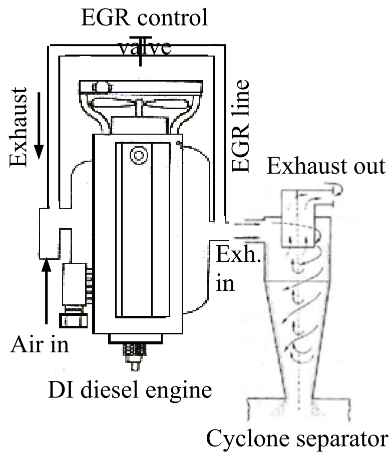

Fig 2: Arrangement of EGR and cyclonic separator

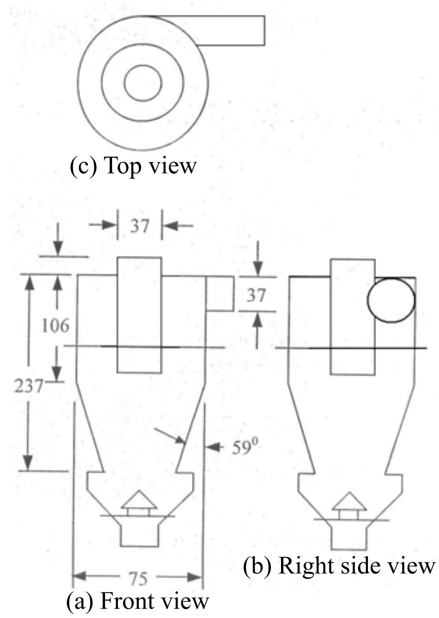

Fig 3: Cyclonic separator on various views
(Dimensions are in mm)

the cylinder tends to become stoichiometric. There is a possibility of making over rich zones in the combustion chamber producing incomplete combustion as well as less maximum combustion temperature. NOx emission without EGR and with 10% EGR rate is increased with engine loads up to ¾ of full load. When the load is further increased to full load, NOx emission is decreased due to less maximum combustion temperature for incomplete combustion. NOx is more reduced at higher engine loads for all EGR rates. NOx reduction with 10% EGR rate is from 52 ppm (at no-load) to 228 ppm (at full load). For 20% EGR rate, NOx is increased up to ½ of full load, but after that NOx is decreased. NOx reduction with 20% EGR rate is from 106 ppm to 791 ppm. For 30% EGR rate, NOx is increased up to ¼ of full load, but after that NOx is decreased. NOx reduction with 30% EGR rate is from 149 ppm to 719 ppm. The lower graph of Fig. 4 shows percent reduction of NOx at different EGR rates for various engine loading conditions and average NOx reduction. At 10% EGR rate, NOx reduction is 20-25% depending on engine loads. The average NOx reduction is about 23%. At 20% EGR rate, NOx reduction is 51-78% and average NOx reduction is about 62%. At 30% EGR rate, NOx reduction is 72-93% and average NOx reduction is about 81%.

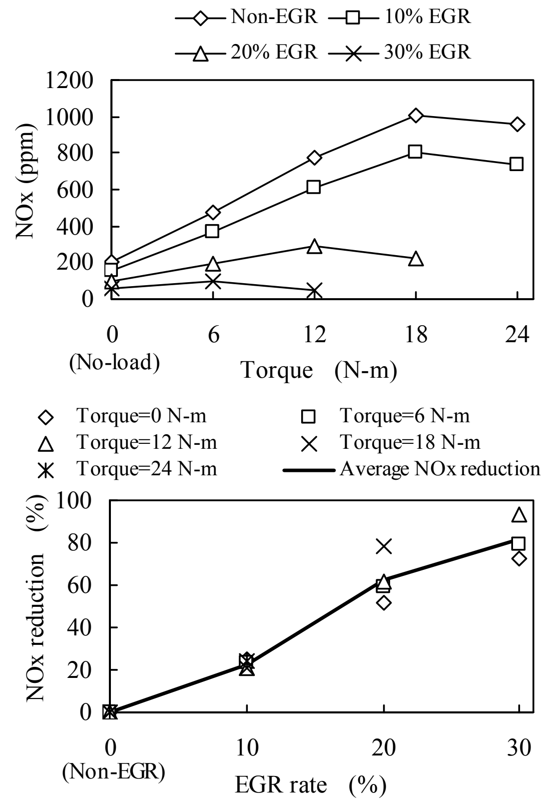

Fig 4: NOx emission at different engine loads without and with EGR and average NOx reduction

Figure 5 shows CO emission without and with different EGR rates for various engine loadings. There is no significant change in CO emission without EGR up to ¾ of full load. The level is about 800 ppm. When the load is further increased to full load, CO emission is increased to 1360 ppm. The similar trend in CO emission with 10% EGR rate is observed, that is up to ¾ of full load, there is no significant change in CO emission and the level is about 900 ppm. When the load is further increased to full load, CO emission is increased to 2000 ppm. With 20% EGR rate, CO level up to ½ load is about 950 ppm, but at ¾ load the level is 2300 ppm. At 30% EGR rate, CO level up to ¼ load is about 1050 ppm, but at ½ load the level is much higher (4500 ppm). The CO data supports the idea that at high EGR rates-high loadings, the combustion becomes incomplete producing much higher CO in exhaust gases. At 10% EGR rate, CO increases 8-47% depending on engine loads. The average CO increase is about 17%. At 20% EGR rate, CO increases 14-170% and average CO increase is about 57%. At 30% EGR rate, CO increases 24-452% and average CO increase is about 175%.

Figure 6 shows PM emission at different engine loadings without and with EGR. The trend of PM emission at different loadings without or with EGR rates and percent increase of PM are very similar to that of CO

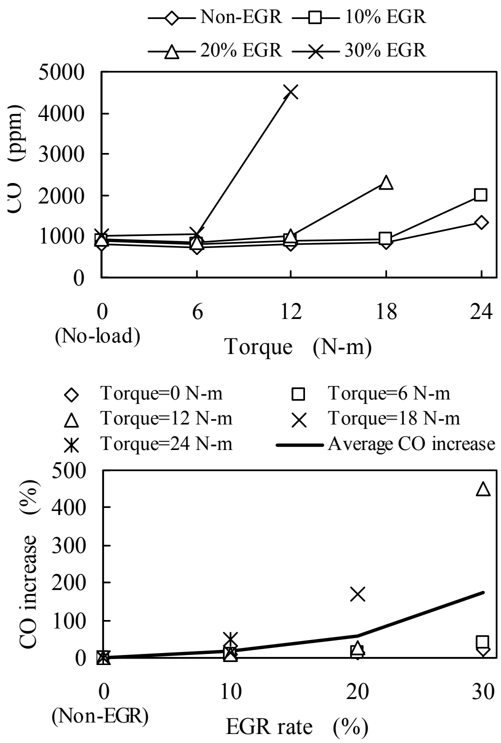

Fig 5: CO emission at different engine loads without and with EGR and average CO increase

emission and percent increase of CO. Actually the in-cylinder condition where there is insufficient oxygen, a large amount of CO is produced. This is also the condition of large amount of PM production. At no-load condition without EGR, the PM emission is about 32 mg/m3. However, PM emission is increased to 551 mg/m3 at full load. At 10% EGR rate, PM emission of about 34 mg/m3 at no-load and 739 mg/m3 at full load is observed. At 20% EGR rate, PM emission of about 44 mg/m^3 at no-load and 980 mg/m^3 at ¾ load is obtained. At 30% EGR rate, PM emission of about 50 mg/m^3 at no-load and 1748 mg/m^3 at ½ load is found. At 10% EGR rate, PM increases 5.5-34% depending on engine loads. The average PM increase is about 19%. At 20% EGR rate, PM increases 37-271% and average PM increase is about 155%. At 30% EGR rate, PM increases 57-1152% and average PM increase is about 521%. It seems that high EGR-high loading conditions are very prone to large amount of PM production.

Figure 7 shows fuel consumption and its increase without and with EGR at different loadings. Although fuel consumption is significantly increased with engine loads, there is not much change in fuel consumption without or with EGR. When engine load is increased from no-load to ¼ load fuel consumption is increased about 45%. When the load is ½ of full load the fuel consumption is about 85% higher than that at no-load condition. When the load is further increased to ¾ of full load the fuel consumption becomes more than double (about 110% increase). However, at full load for non EGR and 10% EGR rate, fuel consumption becomes

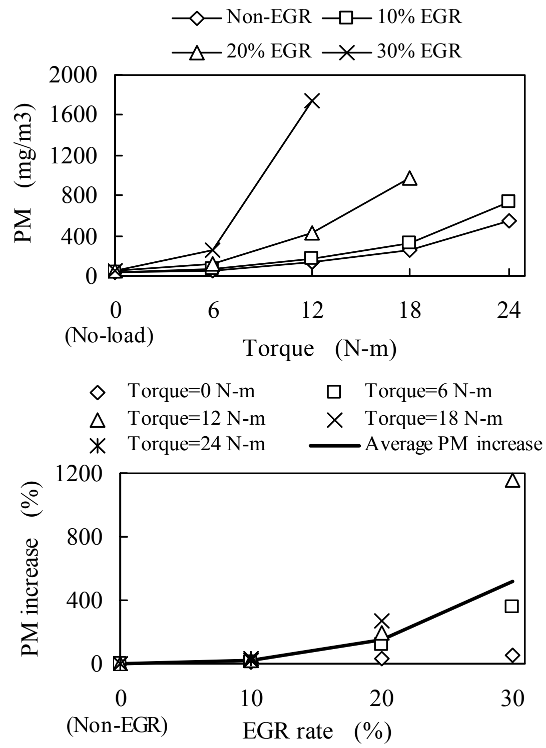

Fig 6: PM emission at different engine loads without and with EGR and average PM increase

three times than no-load condition. At 10% EGR rate, average fuel consumption increases only about 0.5%. At 20% EGR rate, average fuel consumption increases about 2% and at 30% EGR rate, average fuel consumption increase is about 5%.

3.2 Cyclonic Separator Results

Figure 8 shows PM collection by cyclonic separator without EGR and cyclonic efficiency at different engine loading conditions. PM collection without EGR is increased from 32 mg/m^3 at no-load to 551 mg/m^3 at full load. The PM level is decreased to 16 mg/m^3 at no-load and 176mg/m^3 at full load when cyclonic separator is used. The cyclonic efficiency gradually increases from no-load to full load. At no-load condition the efficiency is about 50%, whereas at full load it is about 70%. 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 load conditions.

Figure 9 shows engine backpressure and fuel consumption at different engine loadings without and with cyclonic separator. There is no significant change in engine backpressure with engine loads without or with cyclonic separator. Fuel consumption without separator increases from 0.24 kg/hr at no-load to .71 kg/hr at full load. There is no change in fuel consumption with the use of cyclonic separator.

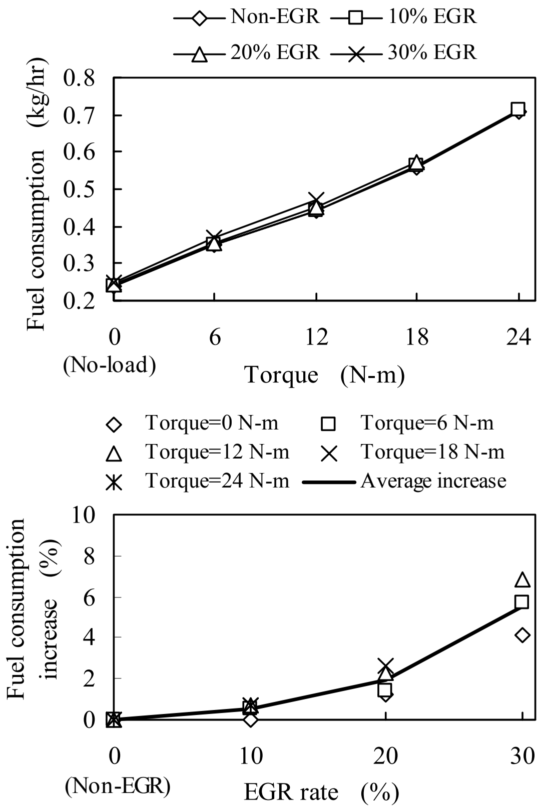

Fig 7: Fuel consumption and its increase at different engine loads without and with EGR

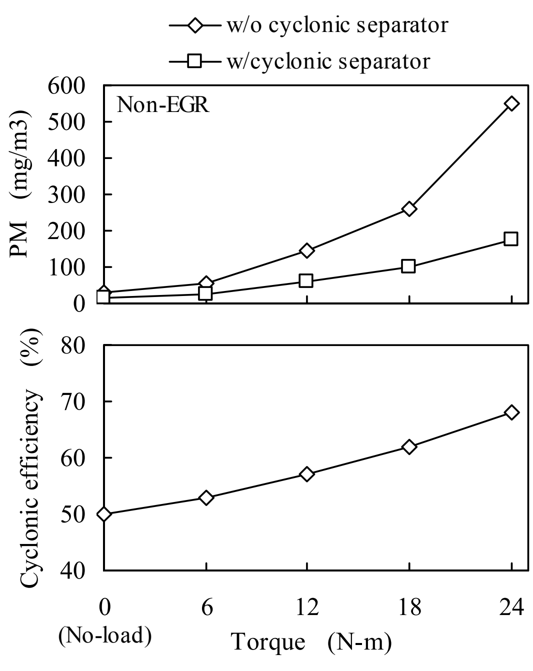

Fig 8: PM collection by cyclonic separator without EGR and cyclonic efficiency at different engine loadings

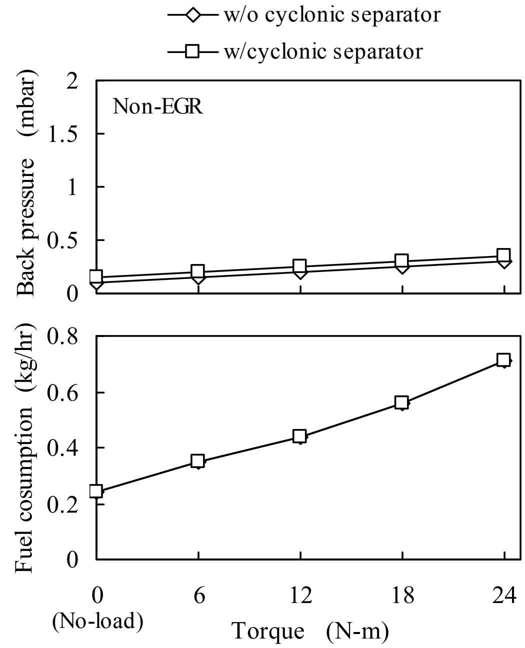

Fig 9: Backpressure and fuel consumption without and with cyclonic separator at different engine loads.

3.3 Combined EGR and Separator Results

Figure 10 shows PM emission for different EGR rates at different engine loadings without and with cyclonic separators. At 10% EGR rate, PM emission at no-load is about 34 mg/m^3. This increases gradually to 739 mg/m^3 at full load. Cyclonic separator removes PM from exhaust and the level at no-load is about 15 mg/m^3 and at full load it becomes 184 mg/m^3. At 20% EGR rate, PM emission at no-load is about 44 mg/m^3 and it becomes 980 mg/m^3 at ¾ load. The level of PM with cyclonic separator at no-load is about 18 mg/m^3 and at ¾ load it becomes 245 mg/m^3. At 30% EGR rate, PM emission at no-load is about 50 mg/m^3 and at ½ load it becomes about 1748 mg/m^3. Cyclonic separator reduces PM from exhaust to the level of 18 mg/m^3 at no-load and 437 mg/m^3 at ½ load.

Figure 11 shows cyclonic efficiency at different EGR rates for different engine loadings. It is found that at higher engine loadings the cyclonic efficiency is higher both for non EGR and EGR conditions. It also shows that with the increase in EGR rate, the cyclonic efficiency is increased. At non EGR condition cyclonic efficiency varies from 50% to 70% depending on engine loads. Cyclonic efficiency increases to 65%-75% at 30% EGR rate. The average cyclonic efficiency at non EGR is 58%, while this increases to 65%, 68% and 70% with 10%, 20% and 30% EGR rate, respectively.

Figure 12 shows average PM emission at different engine loadings and EGR rates with or without cyclonic separator. It shows that average PM emission at non EGR is 208 mg/m^3. It increases to 685 mg/m^3 with 30% EGR rate. When cyclonic separator is used, PM emission reduces to 88 mg/m^3 at non EGR and to 205 mg/m^3 at 30% EGR rate. At 10% EGR rate, the average PM is 55% less than at non EGR and at 20% EGR rate, the average

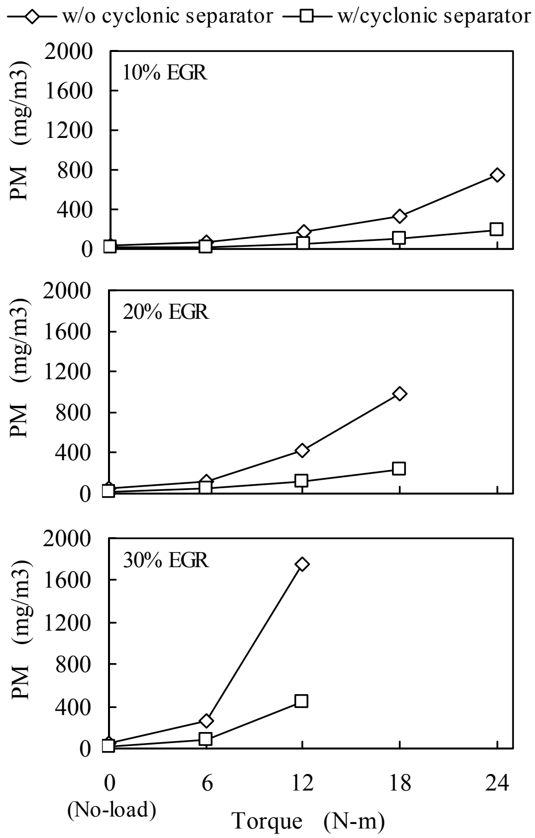

Fig 10: PM emission at different engine loads with different EGR rates

PM is 38% less. Even at 30% EGR rate, the average PM is still 1% less than non EGR level. This implies that if EGR and cyclonic separator are used together, NOx is significantly reduced with no increase of PM. If the main task is NOx reduction, higher percentage of EGR can be applied. However, cyclonic separator must be used.

4. CONCLUSIONS

The following conclusions can be made from the ivestigation.

1) DI diesel engines can be driven in all driving conditions (from no-load to full load) up to 10% EGR rate. At 10% EGR rate, average NOx reduction is about 23%, but CO increases 17% and PM 19% and there is no significant fuel penalty.
2) At 20% EGR rate, average NOx reduction is 62%, but CO increases 57% and PM 155% and there is about 2% fuel penalty.
3) At 30% EGR rate, NOx reduction is more than 80%. However, CO increases 1.75 times and PM increases more than 5 times than non EGR and fuel penalty is about 5%.
4) A simple cyclonic separator can reduce PM from diesel exhaust about 50-70% without hampering other emissions and fuel consumption.
5) Use of EGR and cyclonic separator together can simultaneously reduce NOx and PM from diesel exhaust. In moderate loading condition, 30% EGR rate with cyclonic separator can reduce NOx more

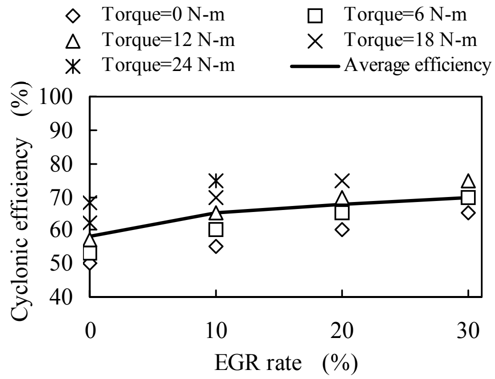

Fig 11: Cyclonic efficiency at different EGR rates for different engine loads

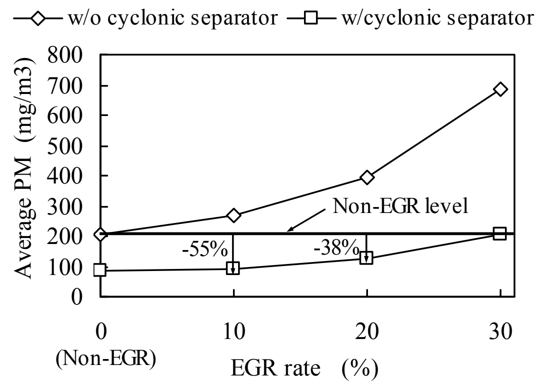

Fig 12: Average PM emission at different engine loads and EGR rates with or without cyclonic separator

than 90% and PM level remains below the level of non EGR condition.

5. REFERENCES

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