

Control of diesel soot and NO_x emissions with a particulate trap and EGR

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Abstract: The exhaust gas recirculation (EGR), coupled with a high-collection efficiency particulate trap to simultaneously control smoke and NO_x emissions from diesel engines were studied. This ceramic trap developed previously provided the soot cleaning efficiency of 99%, the regeneration efficiency reaches 80% and the ratio of success reaches 97%, which make EGR used in diesel possible. At the presence of EGR, opening of the regeneration control valve of the trap was over again optimized to compensate for the decrease of the oxygen concentration in the exhaust gas resulted from EGR. The results indicated the cleaning efficiency and regeneration performance of the trap were maintained at the same level except that the back pressure increased faster.

A new EGR system was developed, which is based on a wide range oxygen (UEGO) sensor. Experiments were carried out under steady state conditions while maintaining the engine speed at 1600 r/min, setting the engine loads at 0%, 25%, 50%, 75% and 100% respectively. Throughout each test the EGR rate was kept at nine different settings and data were taken with the gas analyzer and UEGO sensor. Then, the EGR rate and engine load maps, which showed the tendencies of NO_x, CO and HC emissions from diesel engine, were made using the measured data. Using the maps, the author set up the EGR regulation, the relationship between the optimal amounts of EGR flow and the equivalence ratio, σ , where $\sigma = 14.5/AFR$.

Keywords: particulate trap; EGR; NO_x; soot; UEGO

Introduction

The main pollutants generated from diesel engines are particulates and oxides of nitrogen (NO_x). Significant strides have been made to reduce the amount of particulates. Most investigations employed ceramic honeycomb wall-flow monoliths and were met with considerable success (Mogaka, 1982; Osamu, 1990; Johnson, 1994). However, problems were most often encountered with periodic regeneration (Yiannis, 1990; Paul, 1993; Gantawar, 1997; Mridul, 1999; Matthias, 2000; Ning, 2000). To alleviate such problems, recent work at Dalian University of Technology has employed the infrared regeneration method for diesel exhaust particulate ceramic trap (XU, 2001; 2002). Through real-time control of the exhaust volume for regeneration, the regeneration efficiency reaches 80% and the ratio of success reaches 97%. Particulate collection efficiency of 99% is especially important, which makes it possible to implement EGR without fouling the intake air with particulates, hence, eliminating the danger of damaging internal engine components.

At the presence of EGR, investigations on the cleaning efficiency, the back pressure and regeneration performance of the trap were carried out in this study. Mainly, opening of the regeneration control valve of the trap was over again optimized to compensate for the decrease of the oxygen concentration in the exhaust gas resulted from EGR.

Different means for controlling EGR in diesel engines examined by past investigations have demonstrated the effectiveness of EGR in reducing the NO_x emissions emitted from diesel engines (Dürholz, 1992; Paul, 1998; Kreso, 1998; Baert, 1999). The use of EGR, however, must be optimized in order to maximize the reduction of NO_x and at the same time maintain strong engine performance, low levels of other pollutants, and high fuel conversion efficiency (Throop, 1985; Berry, 1996; Kouremenos, 2001). Research conducted by Narusawa *et al.* (Kazuyuki, 1990) utilized oxygen levels at the intake and exhaust streams to stepwise control the amount of EGR. However, the applied EGR system based on oxygen levels was not accomplished, due to the limitation of the sensor performance.

With the fast response (< 0.1 second) UEGO sensor for the air/fuel ratio (AFR) measurement being commercially available at the present time, this study developed a new closed loop feedback EGR system based on UEGO sensor. This study aims at finding a strategy to govern the electrically controlled EGR valve, which fits the new EGR system nicely.

1 Experimental apparatus and operation

Tests were carried out in a Model 6110 diesel engine. The entire configuration of the test apparatus and the position of the regeneration control valve in different phases are shown in Fig. 1.

For these experiments the infrared regeneration particulate trap was used. A high filtration efficiency (99%) ceramic honeycomb monoliths was used as main trap element. Engine exhaust gas passed through both the trap A and B during the filtration period. The regeneration control valve (RCV) was adjusted in the middle position. While RCV rotated to

a fully close position for the whole exhaust gas to pass through one filter every 20 min, ECU checked whether the back pressure came to the certain guideline value. If it did not come to the certain value, RCV was returned to the middle position again, otherwise ECU converted the filtering mode to the regeneration mode. While one was converted to the regeneration mode, another was still in the filtration mode. The regeneration mode was divided into two phases, the warming up phase and the burning phase. RCV rotated to a fully close position for no exhaust gas to pass through the trap being in the warming up phase of the regeneration mode and ECU turned on the corresponding electrical heater. After the temperature reached 600°C, ECU started to open RCV for a small amount of exhaust gas to be supplied to the trap being in the burning phase of the regeneration mode. The particulates in the trap started to burn and RCV rotated to a degree scale to control the temperature in the trap. This regeneration process was performed for a period of 15 min. After completion of the regeneration, ECU converted the regeneration mode to the filtering mode. ECU repeated this cycle during the engine operation.

The stream of filtered EGR originated at the exit of the particulate trap and was conducted to the intake plenum of the engine. The EGR stream was added to the engine intake just prior to the air filter so that the air filter also provides an extra degree of safety to the engine in case of a leak developed in the trap. The exhaust stream was recirculated without any extraneous pumping action, partly pulled by the intake vacuum, partly pushed by the exhaust stream. The small plenum was used to limit the pressure variations. And the EGR stream was adjusted to a suitable temperature by the water-cooled heat exchanger, which is expected to prevent any significant drop in volumetric efficiency (Paul, 1998). The EGR rate was calculated according to the intake fresh air reduction rate measured by means of the air flow meter. The AFR was measured with a UEGO sensor. NO_x, CO and HC levels were recorded with a gas analyzer. The EGR valve position was controlled using a step motor.

2 Testing procedure and results

Experiments were carried out while maintaining the engine speed at 1600 r/min and setting load respectively at divisions of 0%, 25%, 50%, 75% and 100% of the engine torque. Throughout each test the EGR rate was kept at nine different settings: 0%, 5%, 10%, 15%, 20%, 25%, 30%, 35% and 40% and data were taken.

The EGR rate is calculated as the reduction rate of the inlet fresh air according to the equation given below.

$$\text{EGR rate} = \frac{m_0 - m_{\text{air}}}{m_0}$$

where, m_0 is the flow rate of inlet fresh air without EGR (g/s); m_{air} is the flow rate of inlet fresh air with EGR (g/s).

Fig. 2, Fig. 3 and Fig. 4 show tendencies of NO_x, CO and HC concentrations against EGR rate and load. Because any increase in particulates emission caused by EGR can be eventually controlled with filtration, the tendency of particulates emission was not measured in these experiments.

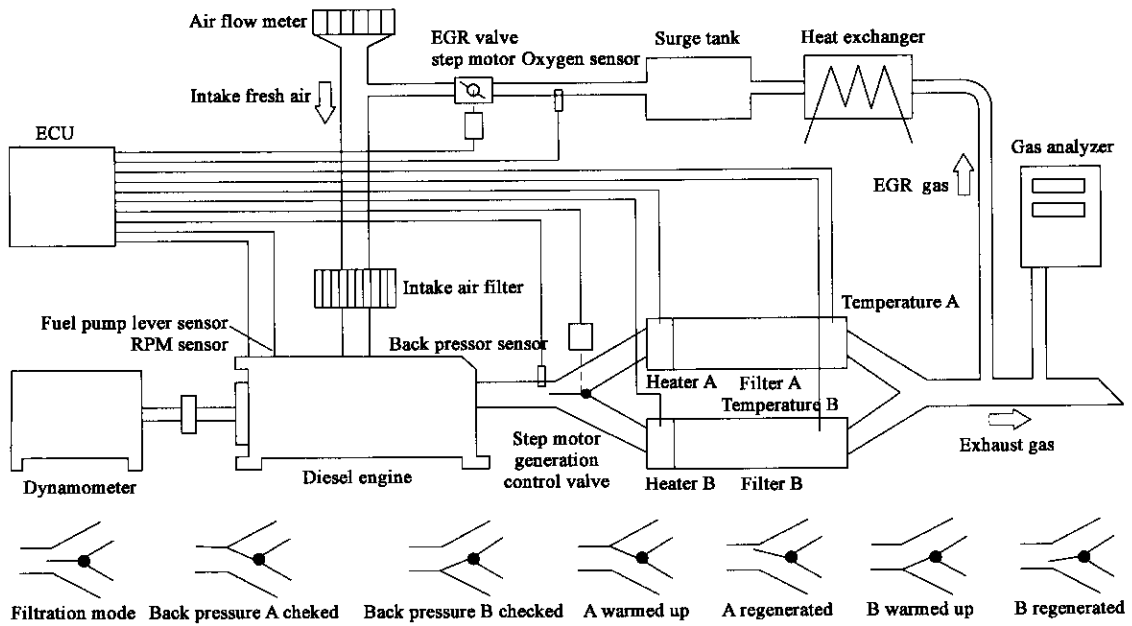


Fig. 1 Schematic of the infrared regeneration particulate trap and EGR system

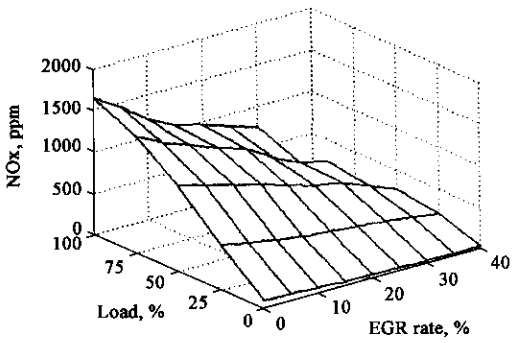


Fig. 2 3-D plot of NOx vs EGR rate and load

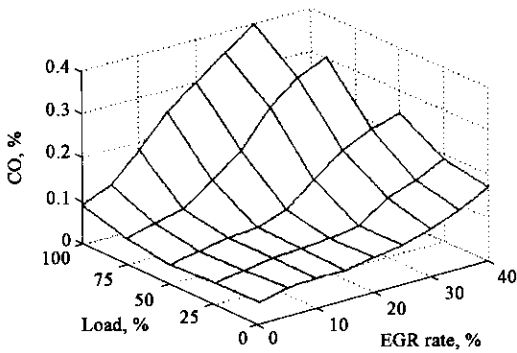


Fig. 3 3-D plot of CO vs EGR rate and load

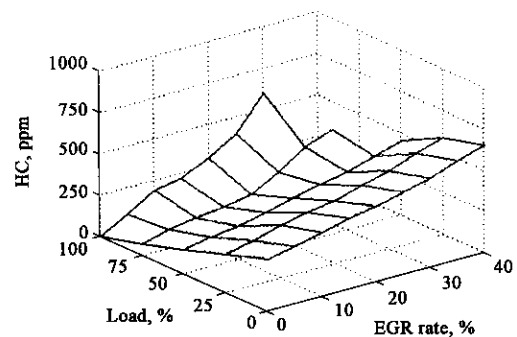


Fig. 4 3-D plot of HC vs EGR rate and load

EGR, while other pollutants increased. At high load EGR was effective at reducing the NOx emissions by over 50% at 20% EGR rate. EGR was not effective in reducing NOx at low loads. At the lightest loads NOx was reduced by several percent only at 20% EGR rate.

The CO increase rate was significant at the heavier loads. At high loads CO emissions were increased by over 50% at 20% EGR. At low to medium loads CO emissions were increased by several percent only.

The concentration of HC emissions was also increased by EGR, showing particularly high increases by high EGR rates at the lower loads.

Fig. 5 shows the tendency of the equivalence ratio, σ . σ was calculated according to the equation given below: $\sigma = 14.5/AFR$, where the air/fuel ratio, AFR, was measured with the UEGO sensor. σ was increased with the increases of EGR rate and load. It can be noticed that an engine which normally does not run in rich fuel condition can be placed in that situation using EGR.

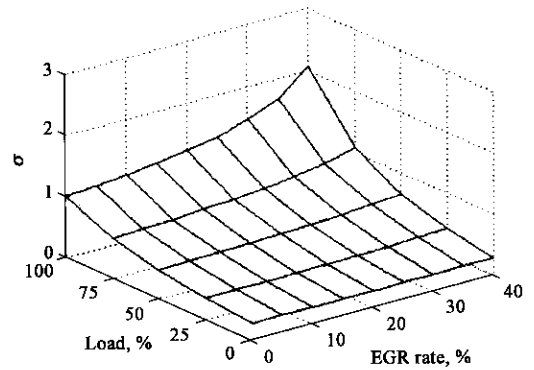


Fig. 5 3-D plot of σ vs EGR rate and load

3 Strategy to control EGR

The results of the previous curves are replotted in Fig. 6, Fig. 7 and Fig. 8 to explore whether there exists a tradeoff between NOx, CO and HC emissions as σ and EGR rate are varied. The same data are given in a two dimensional contour plot to facilitate assessment of values and formulate an algorithm for controlling EGR. The two dimensional curves are replotted in Fig. 9.

In Fig. 9, it can be noticed that NOx and CO depended obviously on σ and EGR rate. First, the effect of σ on NOx and CO was assessed. As σ increased from low values, NOx increased drastically while CO remained approximately constant. At high σ values, NOx remained approximately constant, and CO increased. This effect of σ was more obvious as EGR rate increased. Second, the effect of EGR rate on NOx and CO was explored. Utilizing high EGR rate minimized NOx emissions

The concentration of NOx emissions was effectively reduced by

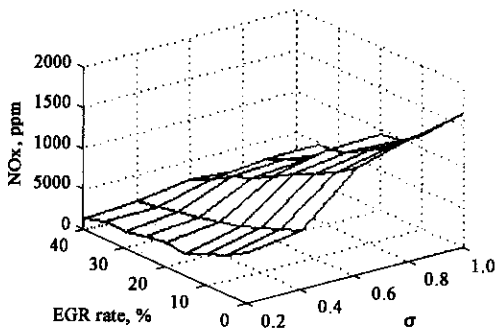


Fig.6 3-D plot of NOx vs EGR rate and σ

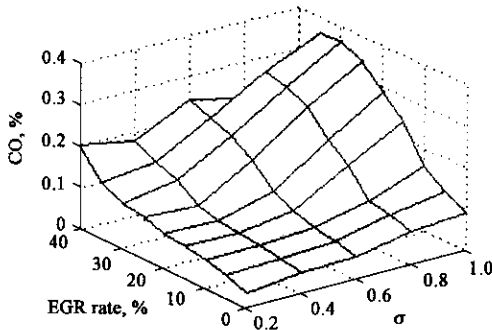


Fig.7 3-D plot of CO vs EGR rate and σ

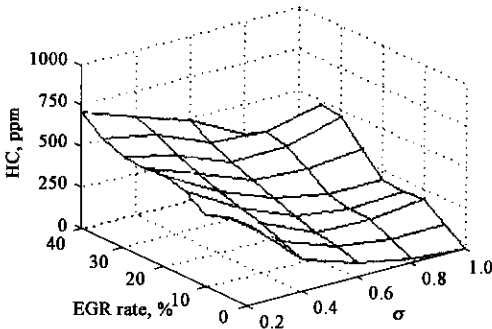


Fig.8 3-D plot of HC vs EGR rate and σ

most effectively, however, because of the deficiency of oxygen, CO increased drastically. Increased CO was most obvious at high σ and high EGR rate. It can also be noticed that the effect of σ and EGR rate on HC was lower than the effect of σ and EGR rate on CO.

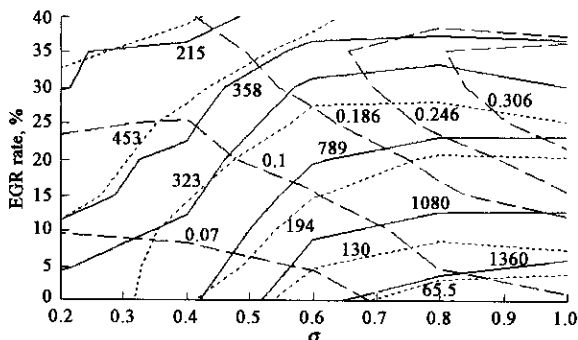


Fig.9 Contour plot of NOx, CO and HC vs EGR rate and σ
 — NOx, 215, 358, 789, 1080, 1360; ---- CO, 0.07, 0.1, 0.186, 0.246, 0.306; HC, 65.5, 130, 194, 323, 453

After all variables being taken into account, an algorithm for controlling EGR was created and depicted in Fig.10. According to this algorithm, the amounts of EGR flow can be determined using AFR, which makes the closed loop feedback EGR system based on UEGO

sensor practical. Compared to the conventional closed loop EGR control with empirically derived engine mapping, which is gradually not exact because the preset optimal engine parameters gradually change as the engine wears, the closed loop feedback EGR system based on UEGO sensor is exact, which adapts well to the change of engine parameters. But these results were based on the tests under a single constant engine speed, more tests under other speeds to verify the results are planned for the near future. The application of the automatically varied EGR system equipped with UEGO sensor to the diesel vehicle in transient operations will also be explored soon.

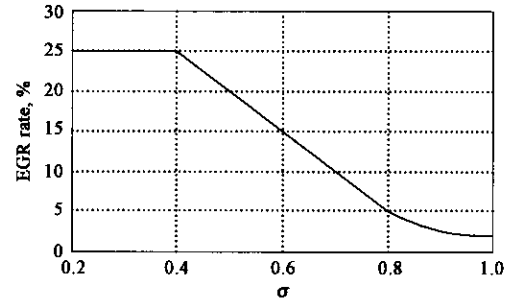


Fig.10 Strategy to control the EGR valve

4 Influence of EGR on the infrared regeneration of trap

The effect of the regeneration of trap can be assessed with the regeneration efficiency. Strictly speaking, the regeneration efficiency should be calculated with the amount of soot trapped after the filtration period and the residual soot that remains unburned after the burning period. The amounts of soot trapped and the residual soot unburned are weighed with a precise electronic scale. In practice, since there is a liner relationship between the amount of soot and the back pressure, the regeneration efficiency can be calculated with the back pressure before and after the burning period. The regeneration efficiency is calculated according to the following equation.

$$\eta = (\Delta p_b - \Delta p_a) / (\Delta p_b - \Delta p_0)$$

where, Δp_0 is the back pressure of the undefiled trap(kPa); Δp_b is the back pressure before the burning period(kPa); Δp_a is the back pressure after the burning period(kPa).

During the regeneration of the trap, burning of the soot in the trap was performed by activating the heater for approximately 15 min and supplying a small quantity of exhaust gas to the trap. Normally, without EGR, an average of 0.25 g (amount of soot/filtration period) was removed from the trap on termination of the burning period, whereas, with EGR, only 0.2 g could be removed when using the same opening of RCV. This means the burning efficiency of soot (regeneration efficiency) reduces 20% at the presence of EGR, and there are some residual soot that remains unburned after the 15 min burning period, because of the decrease of the oxygen concentration in the exhaust gas resulted from EGR. So, at the presence of EGR, opening of RCV should be over again optimized.

To optimize opening of RCV, regenerations of the trap were carried out while maintaining the engine speed at 1600 r/min and setting load at divisions of 0%, 25%, 50%, 75% and 100% of the engine torque respectively. Throughout each of regenerations the EGR rate was automatically regulated to different setting by ECU according to the above algorithm for controlling EGR (Olbrot, 1995). During these regenerations, the influence of opening of RCV on the regeneration efficiency was recorded and compared. Fig. 11 shows the optimum opening of RCV at different loads of the engine. Comparing this result with the previous optimum openings of RCV without EGR, it can be noticed that EGR increases the optimum opening of RCV.

At the presence of EGR, the regeneration efficiency reaches 80 percent again by using the new optimum opening. Fig. 12 shows the temperature curves during the regeneration of the trap when the opening was automatically regulated to different setting by ECU according to the new optimum opening. The temperatures were measured with six type K thermal couples located in the different places of the ceramic monolith. The location of the thermal couples in the ceramic monolith is shown in Fig.13. In Fig.12, it can be noticed that the highest temperature in the different places of the ceramic monolith are 600—900°C, within which

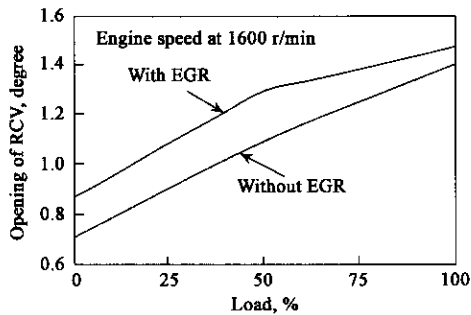


Fig. 11 Optimum opening of the regeneration control valve

range the soot could be burned completely and thermal failures by cracking and melting the ceramic monolith could be avoided.

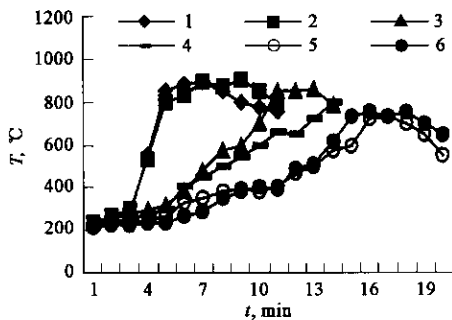


Fig. 12 Temperature curves during the regeneration of the trap

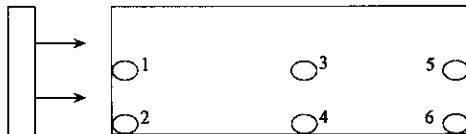


Fig. 13 Schematic of the location of the thermal couples in the ceramic monolith

Finally, the influence of EGR on the back pressure of the trap during the filtration period is explained simply. Since the increase in soot emission caused by EGR varies with the engine operating condition and EGR rate, the back pressure increases at the different rate. Fig. 14 shows the back pressure curves during the filtration period while maintaining the engine speed at 1600 r/min and load at 50% of the engine torque and EGR rate regulated to 20% by ECU. Comparing this result with the previous back pressure curve without EGR, it can be noticed that the back pressure increases faster by a factor of 10.

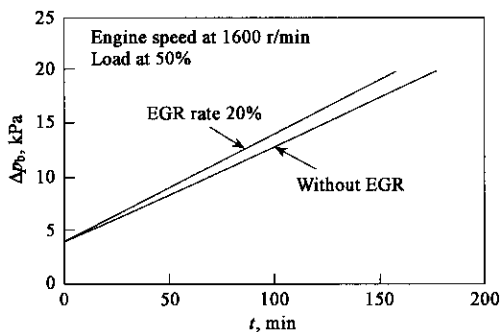


Fig. 14 Back pressure curves during the filtration period

5 Conclusions

At the presence of EGR, by optimizing over again opening of the regeneration control valve of the trap, the cleaning efficiency and regeneration performance of the trap are maintained at the same level except that the back pressure increases faster.

During the regeneration of the trap, the temperature in the different places of the ceramic monolith are 600–900°C, within which range the soot can be burned completely and thermal failures by cracking and

melting the ceramic monolith can be avoided.

EGR is effective in reducing NO_x. Over 50% decrease in NO_x is achieved at 25% EGR and high σ , while CO rises by over 50%.

The maps made using experimental results indicated that NO_x and CO depend obviously on σ and EGR rate. σ can be used to predict the mixture and combustion conditions of the engine.

The optimum EGR control method, which is capable of attaining the highest possible NO_x reduction without causing substantial increases in CO and HC emissions, was established.

The new EGR system equipped for the first time with the UEGO sensor can be made practical with the optimum EGR control method. It is a simple but effective solution.

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