

Effect of Exhaust Catalysts on Regulated and Unregulated Emissions from Low Temperature Diesel Combustion with High Rates of Cooled EGR

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ABSTRACT

Unregulated emissions from a DI diesel engine with ultra-high EGR low temperature combustion were analyzed using Fourier transform infrared (FTIR) spectroscopy and the reduction characteristics of both regulated and unregulated emissions by two exhaust catalysts were investigated. With ultra-high EGR suppressing the in-cylinder soot and NO_x formation as well as with the exhaust catalysts removing the engine-out THC and CO emissions, clean diesel operation in terms of ultra-low regulated emissions (NO_x, PM, THC, and CO) is established in an operating range up to 50% load. To realize smokeless low temperature combustion at higher loads, EGR has to be increased to a rate with the overall (average) excess air ratio less than the stoichiometric ratio. As a result, the thermal efficiency severely deteriorates, the THC and CO emissions drastically increase, and although approximately 50% reductions in THC and CO are obtained with the exhaust catalysts, these emissions are still high in the ultra-high EGR smokeless low temperature combustion regime. The unregulated emissions increase drastically with intake oxygen content below 14% due to EGR. These trends correlate well with the drastic increases in THC emissions. The exhaust catalysts are effective to reduce some unregulated toxic emissions including aldehydes and some unsaturated hydrocarbons. However, aromatics and methane generated from ultra-high EGR low temperature smokeless combustion are hardly reduced with the catalysts, particularly under overall rich conditions. Catalysts of higher oxidation ability can help to further reduce methane and aromatics to some degree but these emissions are still at high levels due to the low temperature combustion operation with ultra-high EGR.

INTRODUCTION

To meet the increasingly stringent regulations in North America, Europe, and Asia, exhaust gas aftertreatment devices for diesel engines has become inevitable. Meanwhile, from the viewpoint of maintaining the functioning of exhaust aftertreatment devices and fuel

economy in terms of vehicle running cost, a further reduction in the engine-out exhaust emissions through advanced combustion technologies are urgently required. Conventionally, the challenge in achieving cleaner diesel combustion is to simultaneously reduce NO_x and smoke emissions. Exhaust gas recirculation (EGR) is effective to reduce NO_x emissions from diesel engines, but because of the trade-off between NO_x and smoke emissions, EGR is conventionally limited to relatively low rates despite the potential for further reductions in NO_x emissions. Recently, Akihama et al. reported smokeless rich diesel combustion where simultaneous reductions of smoke and NO_x emissions are realized by ultra-high rates (> 60%) of EGR [1] and similar concepts for low temperature diesel combustion have been investigated and developed at institutions worldwide [2-10]. One concern with ultra-high EGR smokeless combustion is the much higher CO and THC emissions compared with conventional diesel combustion. The CO and THC emissions can be removed using oxidation catalysts and these emissions can also be utilized to regenerate NO_x trap catalysts. However, research has demonstrated that some unregulated toxic emissions including aldehydes and aromatics are very closely related to THC emissions [11]. Further, in subjective sensing tests with the exhaust gas from ultra-high EGR smokeless diesel combustion, the authors here experienced strong unpleasant odors and eye irritation, implying the presence of high concentrations of aldehydes and aromatics in the exhaust gas. In addition, other researches have reported that unusually high concentration of aromatics or PAHs (polycyclic aromatic hydrocarbons) were observed even after passage of the exhaust catalysts with the engines running on rich combustion by large rates of EGR [12-13]. Therefore, special attention must be paid to these unregulated toxic emissions when utilizing ultra-high EGR as a strategy to simultaneously reduce NO_x and smoke or to generate a rich mixture to regenerate NO_x trap catalysts.

This study, first, analyses and discusses the characteristics of both regulated and unregulated emissions and the effects of the exhaust catalysts at

50% load. Then, these characteristics at 40% and 60% loads are investigated. Finally, the effect of the exhaust catalysts of higher oxidation ability on these emissions are examined.

EXPERIMENTAL APPARATUS AND PROCEDURES

Figure 1 shows a schematic of the experimental setup. Table 1 shows the engine specifications and Figure 2 shows the piston bowl geometry and injection nozzle arrangement. Experiments were conducted on a single cylinder, naturally aspirated, four-stroke cycle, 1.0 L DI diesel engine with a common rail fuel injection system. The fuel injection timing was controlled such that the ignition timing (start of high temperature oxidation) was maintained at TDC (top dead center) regardless of EGR rate. The injection pressure was set at 120 MPa. The swirl and compression ratios were 2.2 and 16, respectively. The test fuel is JIS#2 sulfur-free (< 10 ppm) diesel fuel. The fuel injection quantity Q_f was set at 27, 32, and 37 mm³/stroke corresponding to 40, 50 and 60% loads (indicated mean effective pressure (IMEP): 0.4, 0.5, and 0.6 MPa) under no EGR conditions. These injection quantities, when the engine operating with ultra-high EGR smokeless combustion, are representatives of lean, stoichiometric and over-rich conditions by the overall (average) excess air ratios λ . The engine speed and coolant temperature were fixed at 1320 rpm and 80°C, respectively. The EGR was realized by diverting part of the cooled exhaust gas into the intake port with gate valves. The EGR rate was defined by

$$EGR\ rate = (M_{air0} - M_{air}) / M_{air0}$$

where M_{air0} and M_{air} are mass flow rates of the intake fresh air without and with EGR. The flow rate of intake fresh air was obtained by using a manometer to measure the pressure difference between the inlet and outlet of an orifice on the intake surge tank. The temperature of the mixture of the intake fresh air and EGR gas was around 30°C under all operating conditions. A commercial exhaust catalyst (A) for passenger diesel cars was set 600 mm downstream from the engine exhaust exit. To examine the effect of oxidation ability of the catalyst on the emissions, an oxidation catalyst (B) of higher oxidation ability was also used. Table 2 shows the specifications of the two catalysts.

The exhaust gas was analyzed with an automotive exhaust gas analyzer (MEXA-8120: HORIBA) including NDIR (non-dispersive infrared absorption) for CO and CO₂, CLD (chemical luminescence detector) for NOx, and HFID (heated flame ionization detector) for THC. The oxygen concentrations in the intake and exhaust gases were measured with a paramagnetic type portable oxygen tester (POT-101: SHIMAZU), and the smoke concentration was measured with a Bosch-type smoke meter (DSM-20AN: ZEXEL), and it is presented by the transparency of light through a filter paper where smoke

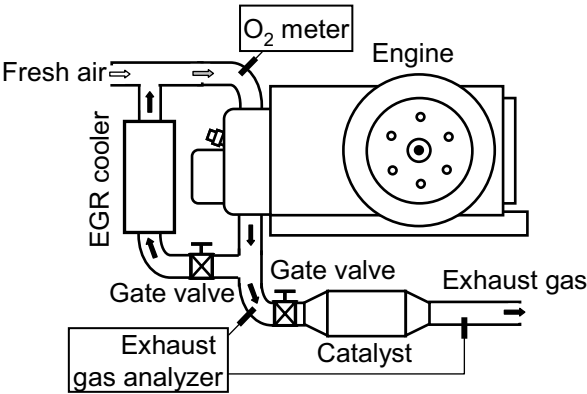


Fig. 1 Experimental setup

Table 1 Engine specifications

Cylinder number	1
Bore × Stroke	ϕ 110 × 106 mm
Displacement	1007 cm ³
Piston cavity shape	toroidal
Compression ratio	16.0
Swirl ratio	2.2
Intake system	Naturally aspirated
Valve number	2
Fuel injection system	Common rail system
Nozzle hole	ϕ 0.20 × 4 -150°

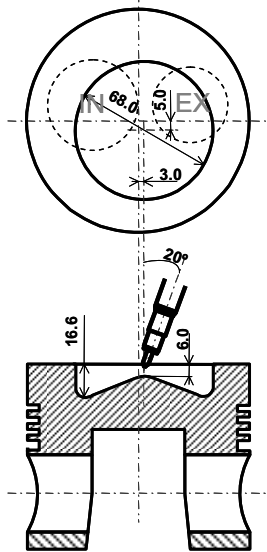


Fig. 2 Piston bowl geometry and injection nozzle arrangement

Table 2 Catalysts specifications

	Catalyst A	Catalyst B
Volume (L)	2.3	2.0
Frontal area (cm ²)	80	130
Substrate	Metal foil	Ceramic
Cell density (cpsi)	400	400
Coating	Pt base	Pt base
Aging	Fresh	Fresh

is sampled. The base value is -3.5%, therefore a negative value is resulted when there is no smoke or/and smoke concentration is very low. The particulate matter (PM) was sampled by a partial flow type dilution tunnel ($\phi 310 \times 3100$ mm) and a constant volume sampler (CVS). The dilution ratio, which was determined by the concentration ratio of CO_2 in the engine exhaust pipe and dilution tunnel, was maintained at around 10 by adjusting the exhaust gas flow rate into the dilution tunnel. Teflon-coated glass fiber filters (203×254 mm) were used for the total particulate matter (TPM) sampling. The total PM was measured by weighing the filter mass before and after sampling. The soluble organic fraction (SOF) was measured by the filter soak method [14] with dichloromethane as a solvent. The unregulated toxic emissions including aldehydes, 1,3-butadiene and aromatics, and some low molecular hydrocarbons were measured by Fourier transform infrared spectroscopy (FTIR) (MEXA-4100 FT; HORIBA).

RESULTS AND DISCUSSION

THE EFFECT OF THE EXHAUST CATALYST ON REGULATED AND UNREGULATED EMISSIONS AT 50% LOAD

Figure 3 shows the indicated thermal efficiency η_i and the effect of the exhaust catalyst (A) on the regulated emissions with large rates of cooled EGR at 50% load. The abscissas indicate the intake oxygen content changed with EGR and the EGR rate. The stoichiometric line is drawn to evaluate the minimum oxygen needed to completely burn the injected fuel. The indicated thermal efficiency does not change significantly over a wide range of EGR, and it decreases only a little with 60% EGR or 8% intake oxygen, where the smokeless and ultra-low NO_x combustion is realized. This may be a result of competition between the deterioration of combustion efficiency and the reduction in cooling loss due to the lowered combustion temperature [7-10]. Without EGR, catalyst (A) causes NO_x to decrease somewhat due to the fact that catalyst (A) has some de NO_x function. With EGR increasing, the de NO_x effect of the catalyst becomes indiscernible, and NO_x almost disappears with the EGR rate higher than 40% or the intake oxygen content lower than 14%. Smoke increases initially, reaches a peak around 12% intake oxygen, and decreases with the intake oxygen decreasing by EGR, and smokeless combustion is established with 8% intake oxygen. Though the effect of catalyst (A) on smoke is not apparent with the intake oxygen higher than 12%, it causes smoke to decrease to some degree with 8-12% intake oxygen. The THC and CO show no apparent changes with the intake oxygen higher than 14%, and they increase drastically with the intake oxygen decreasing to lower than 14%. With catalyst (A), THC is suppressed to values lower than $0.3 \text{ g}/(\text{kW}_i \cdot \text{h})$ while CO almost disappears even at 8% intake oxygen.

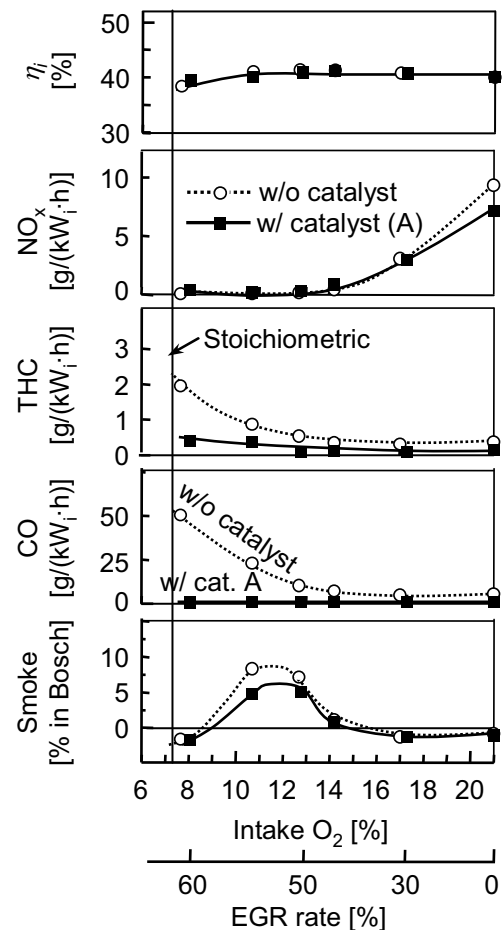


Fig. 3 The indicated thermal efficiency and the effect of catalyst (A) on regulated emissions with large rates of cooled EGR ($Q_f = 32 \text{ mm}^3/\text{stroke}$)

Figure 4 shows the inlet and outlet temperatures of catalyst (A) and the effect of catalyst (A) on the exhaust O_2 concentration and NO fraction in NO_x under the same conditions as in Fig. 3. NO_x is mainly comprised of NO and NO_2 . Therefore one can easily deduce the change of NO_2 fraction in NO_x by subtracting NO fraction from unity. Without catalyst (A), NO fraction in NO_x is higher than 80% and it increases with the EGR rate higher than 40% while NO_x decreases to lower than $0.27 \text{ g}/(\text{kW}_i \cdot \text{h})$. With catalyst (A), NO_2 shows apparent higher fraction than NO with the intake oxygen higher than 14%. On the catalyst surface NO_2 is deoxidized by CO and HC more easily than NO , this could result in the reduction of NO_x shown in Fig. 3. However the detailed mechanism of the NO_x reduction needs further research. With intake oxygen lower than 14% by increasing EGR NO becomes dominant in the catalyst-out NO_x . This is attributed to the fact that the drastic increases of THC and CO by which NO_2 would be precedently deoxidized compared with NO . The catalyst temperature T shows no significant changes at intake oxygen higher than 12%, however it increases greatly with the intake oxygen lower than 12%. This can be attributed to the drastic increases of the THC and CO emissions with the intake oxygen lower than 12%. The increased temperature may help to