



Effect of Exhaust Gas Recirculation Rate on the Emissions of Persistent Organic Pollutants from a Diesel Engine

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ABSTRACT

This study investigates the emission characteristics of toxic organic pollutants (PAHs, PCDD/Fs, and PCBs) generated by a heavy-duty diesel engine operating at various exhaust gas recirculation (EGR) rates during steady-state cycles. Tests on the exhaust gas composition were conducted before and after changing the EGR ratio. The fuel used in the study (B2 diesel) was a mixture of 2% biodiesel and 98% diesel. The main focus was on the emission factors for the organic toxic pollutants in the exhaust gas after EGR ratios of 0% and 5% were applied. At an EGR ratio of 5%, the total mass emission factors for the PAHs and PCBs increased by 9.1 times and 14.4 times, respectively, while the toxicity equivalent factors increased by 4.0 times and 4.8 times, respectively. A significant increase in pollutants with a higher molecular weight, particularly for the PAHs, was observed after applying an EGR ratio of 5%, implying incomplete combustion. The emission factors of carbon dioxide (CO₂) and nitric oxides (NO_x) decreased by 2.5% and 54.4%, respectively, when the EGR ratio was increased from 0% to 5%, but those of PM and carbon monoxide (CO) increased by 60.5% and 66%, respectively. Therefore, a combination of control strategies is necessary in order to achieve a significant reduction in the emission of all pollutants.

Keywords: EGR; PCDD/Fs; PAHs; PCBs; Diesel engines; Engine emissions.

INTRODUCTION

Diesel engines are among the major sources of “criteria” pollutants such as nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO), and total hydrocarbons (HC) (Popovicheva *et al.*, 2014). In addition, inventories have shown that they contribute greatly to ambient air concentrations of toxic persistent organic pollutants (POPs), for example, polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs), polychlorinated biphenyls (PCBs), polybrominated biphenyl dibenzo-*p*-dioxins and dibenzofurans (PBDD/Fs), and polybrominated diphenyl ethers (PBDEs) (Wang *et al.*, 2008; Guido *et al.*, 2013; Zhao *et al.*, 2018a). Previous studies have shown that the relative mass concentrations of the POPs in reported diesel engine exhausts rank as follows: PBDEs > PBDD/Fs > PCBs >

PCDD/Fs (Chang *et al.*, 2014; Rajesh Kumar and Saravanan, 2015).

European emissions regulations are forcing automobile diesel engine manufacturers to find more sophisticated ways to reduce emissions, especially nitrogen oxides (NO_x) and particulate matter (PM) (Maiboom *et al.*, 2009). Exhaust gas recirculation (EGR) is a reputable practice for reducing the concentration of NO_x in the emissions (Maiboom *et al.*, 2009; Chang *et al.*, 2014). The NO_x reduction mechanisms applied in EGR involve complex and sometimes reverse processes that occur during combustion (Rajesh Kumar and Saravanan, 2015). Actual EGR systems often result in uneven distribution of emissions from cylinder to cylinder, with air and recirculated exhaust gas not being completely mixed, which has an effect on other pollutants (Wu *et al.*, 2014; Subbarayan and Senthil Kumar, 2017). Subbarayan and Senthil Kumar (2017) tested a cottonseed biodiesel blend for cold and hot EGR rates based on injection pressure and injection time and observed a significant increase in emissions of HC, smoke opacity, and NO_x. However, under varying load conditions, the high-temperature EGR rate was associated with lower emissions as compared to the cold EGR rate (Chang *et al.*, 2013b; Redfern *et al.*, 2017a). Application of fuel blends is a viable technique in

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pollution control. Overall, biodiesel and bio-alcohols (such as ethanol and butanol) have higher brake thermal efficiency (BTE) and lower emissions for carbon monoxide (CO), particulate matter (PM), and hydrocarbons (HC) (Weber and Kuch, 2003; Wang *et al.*, 2009). However, biodiesels produce more nitrogen oxide (NO_x) emissions than fossil-based diesel, which has the ability to reduce NO_x emissions owing to its huge heat of vaporization (Chang *et al.*, 2013a). PM emissions from diesel engines provide carbon sources for the formation of PAHs and a large surface area for adsorption of other toxins in the ambient air (Liu *et al.*, 2013).

According to Wang *et al.* (2003), POPs pose huge risks to human health and despite their emission levels being at very low concentrations, their importance as toxic pollutants in the atmosphere should not be ignored especially in the case of PCDD/Fs, which have been referred to as the poison of the century (Liu *et al.*, 2016). The lethality of dioxins (PCDD/Fs) has been proven through a large number of animal experiments, with estimations showing that their toxicity is 130 times that of cyanide and 900 times that of arsenic (Ebert and Bahadir, 2003; Redfern *et al.*, 2017b). After entering and accumulating in the human body, dioxins are believed to adversely affect human health, for example, through destruction of the immune system and initiation of cancer (Xing *et al.*, 2017; Zhao *et al.*, 2018b).

Even though the research on toxic and carcinogenic pollutants emitted by diesel engines is still relatively scarce, investigations on the pollutants emitted by diesel engines have been ongoing for decades (Chang *et al.*, 2014). The International Agency for Research on Cancer (IARC) classifies the toxic pollutants emitted by diesel engines under the first group of human carcinogens. Because air pollution control is among the main strategies in the plan for control and prevention of cancer, efforts are underway to cut the emissions from diesel engines (Wang *et al.*, 2007; Chang *et al.*, 2014).

This study is aimed toward investigating the effects of different EGR ratios on the emissions from a heavy-duty

diesel engine at a steady-state. Studies on emissions from diesel engines have been carried out for many years. However, to the best of our knowledge, no such studies have focused on the effect of different EGR ratios on the emissions from a diesel engine running at a steady state. Efforts were thus made herein to discuss the exhaust emission characteristics of organic toxic pollutants, especially PAHs, PCDD/Fs, and PCBs, in the exhaust gases emitted by diesel engines after changes in the EGR rate.

METHODS AND MATERIALS

Diesel Engine

For the experiment, a six-cylinder diesel engine was used with the following specifications: naturally aspirated, water-cooled, 6-liter direct-injection, and heavy-duty. Further specifications of the diesel engine and the boundary conditions during the operation are listed in Table 1. An engine dynamometer was used to control the engine's speed and torque. In this experiment, the diesel engine was monitored under four modes of operation out of the possible thirteen European Steady-State Cycle (ESC) modes: the 1st Mode (750 rpm, 0 Nm), 2nd Mode (1650 rpm, 360 Nm), 7th Mode (1650 rpm, 90 Nm), and 11th Mode (1950 rpm, 96.2 Nm).

Sampling Procedures

For collection of the test emissions, runs were made using B2 fuel (98% fossil diesel and 2% biodiesel); EGR rates were set at 0% and 5%, and the cycle was repeated. The engine was started and left to run for 30 minutes before each sample was taken and for at least 3 minutes between the selected test modes. After each EGR rate change, the engine was preconditioned in the 11th mode for 30 minutes. During each entire test cycle, the exhaust gases of the diesel engine were sampled right away and at equal speeds using a sampling system consisting of a flow meter, a fiberglass filter, a condenser, a two-stage glass cylinder,

Table 1. A summary of the important parameters of the diesel engine under investigation.

Item	Hino W06E
Configuration	In-line 6-cylinder
Stroke	118 mm
Broe	104 mm
Air intake	Naturally aspirated
Compression ratio	17.9
Type of fuel injection system	Bosch A type
Injection type	Direct injection
Fuel injection pressure	21,560 kPa
Injection timing	15 before top dead center
Displacement	6.0 L
Max torque	412 Nm @ 1800 rpm
Max power	121 kW @ 3000 rpm
EGR	No
Boundary condition	
Ambient air temperature	30–40°C
Ambient air pressure	Approximate 101 kPa (1 atm)
Ambient air humidity	60–70%

and a pump. The emission particle phases were captured using a fiberglass filter. A condenser located in front of the two-stage glass cylinder was used to cool the exhaust gas to a temperature below 5°C, and the moisture was then extracted from the exhaust gas. The gas phase contaminants were then collected using a two-stage glass cylinder. A box with 2.5 cm polyurethane foam plugs at each end was filled with 5.0 cm of XAD-2 resin, which weighed about 20 g.

The analytes were concentrated by combining the four samples collected in the ESC mode to ensure that the analyte concentration was above the detection limit. The total sampling time was approximately 80 minutes (approximately 20 minutes per ESC mode). Finally, the sampled flue gas volumes were consolidated under the following physical conditions: a pressure of 760 mmHg and a temperature of 273 K.

Pre-treatment of Samples and Quality Assurance

Before the sampling process, the glass fiber filter was exposed to an oven temperature of 450°C for a duration of 8 hours to get rid of any possible organic matter. The POPs in the blank samples did not exceed 0.5% of the total POPs in the actual exhaust samples, with the exception of PBDEs, which were less than 2%. The concentrations of the pollutants of interest in the blank samples were thus insignificant compared to the corresponding exhaust samples.

The sampling system was tested for leakage in the section lying between the filter holder's inlet and the flow meter's outlet prior to each fuel test. In the preceding sampling exercise, a breakthrough test was performed on PAHs using a three-stage glass filter. From the results, it was clear that 16 specific PAHs in the third stage only accounted for between 0.409% and 4.37% of all three stages. Consequently, the two-stage glass filter applied in this investigation ensured a collection efficiency of 95%. The XAD-2 resin was spiked with an isotopically categorized PCDD/F in order to replace the standard prior to sampling at the exhaust. The recovery rate of PCDD/F replacement standard ranged between 90% and 94%, which was in line with the recovery standard of U.S. EPA Method 23 (70–130%). This recovery indicates that the breakthrough of PCDD/F was negligible. It was not possible to purchase alternative standards for other analytes; therefore, the corresponding PCDD/F was used for the PBDD/F sampler collection efficiency check instead of the

standard recovery rate. The corrections for the sampler collection efficiencies in the concentrations of other chemical species reported in this study were not done.

Prior to the extraction process, the $^{13}\text{C}_{12}$ -labeled internal standard depicted in Table 2 was incorporated into the extract for the quantification of the sample and monitoring of its recovery in the analytical procedure. Addition of the recovery standard solution to the sample prior was necessary during the instrumental analysis to ensure recapture in the analysis. Relevant standards were applied for the precision and recovery (PAR) of the POPs, replacements, and internal and recycling practices. A signal-to-noise ratio (S/N) greater than 3 was applied as the limit of detection (LOD) in this study. Meanwhile, an S/N greater than 10 was applied as the limit of quantitation (LOQ). Another assumption used for this investigation was that the undetected homologues were 50% of the LOD for the PAHs and PBDEs, while for the PCDD/Fs, PCBs, PCDEs, PBDD/Fs, and PBBs the undetected homologues were equal to 0.

Instrumental Analysis

The concentrations of PAHs were measured using Agilent 5890A and 5975 series GC/MS, which were equipped with capillary columns (50 m × 0.32 mm × 0.17 μm, HP Ultra 2). Earlier operating conditions applied by Chang *et al.* (2014) were also used for this investigation as follows: a splitless 1 μL injection at a temperature of 300°C, with an ion source temperature of 310°C. A 45°C furnace temperature was maintained for 1 minute and then raised to a temperature of 100°C within 5 minutes. Afterwards, the temperature was increased from 100°C to 320°C at a rate of 8°C per minute, and then it was kept at 320°C for 15 minutes. For the primary and secondary PAH ions, a scan mode for the pure PAH standard was used to establish their masses. The selected ion monitoring (SIM) mode was used to qualify the PAHs.

A high-resolution gas chromatography/mass spectrometer (HRGC/HRMS) was applied in the analysis of the remaining persistent contaminants. A silica capillary column (J&W Scientific, CA, USA) and a splitless injector were fitted in the HRGC (6970 series gas; Hewlett-Packard, CA, USA) while the HRMS (Autospec Ultima; Micromass, Manchester, UK) was fitted with a positive electron impact (EI+) source. The resolution power of the SIM mode was 10,000. The source temperature was 250°C, and the electron

Table 2. The internal standards used for the study.

Analytes	Homologue
PAHs	d_8 -Nap, d_{10} -Acp, d_{10} -PA, d_{12} -CHR, and d_{12} -PER
PCDD/Fs	$^{13}\text{C}_{12}$ -2,3,7,8-TeCDD, $^{13}\text{C}_{12}$ -1,2,3,7,8-PeCDD, $^{13}\text{C}_{12}$ -1,2,3,6,7,8-HxCDD, $^{13}\text{C}_{12}$ -2,3,7,8-TeCDF, $^{13}\text{C}_{12}$ -1,2,3,7,8-PeCDF, $^{13}\text{C}_{12}$ -1,2,3,6,7,8-HxCDF, $^{13}\text{C}_{12}$ -1,2,3,4,6,7,8-HpCDD, $^{13}\text{C}_{12}$ -OCDD, $^{13}\text{C}_{12}$ -1,2,3,4,6,7,8-HpCDF
PCBs	$^{13}\text{C}_{12}$ -PCB-77, -81, -105, -114, -118, -123, -126, -156, -157, -167, -169, and -189
PCDEs	$^{13}\text{C}_{12}$ -CDE-37, -86, -141, and -180
PBDD/Fs	$^{13}\text{C}_{12}$ -2,3,7,8-TeBDF, $^{13}\text{C}_{12}$ -1,2,3,7,8-PeBDF, $^{13}\text{C}_{12}$ -2,3,4,7,8-PeBDF, $^{13}\text{C}_{12}$ -1,2,3,4,7,8-HxBDF, $^{13}\text{C}_{12}$ -1,2,3,4,6,7,8-HpBDF, $^{13}\text{C}_{12}$ -OctBDF, $^{13}\text{C}_{12}$ -2,3,7,8-TeBDD, $^{13}\text{C}_{12}$ -1,2,3,7,8-PeBDD, $^{13}\text{C}_{12}$ -1,2,3,4,6,7,8-HxBDD, $^{13}\text{C}_{12}$ -1,2,3,7,8,9-HxBDD, $^{13}\text{C}_{12}$ -1,2,3,4,6,7,8-HpBDD, $^{13}\text{C}_{12}$ -OctBDD
PBBs	$^{13}\text{C}_{12}$ -PBB-52, -153, -194, and -209
PBDEs	$^{13}\text{C}_{12}$ -BDE-28, -47, -99, -154, -153, -183, -197, -207, and -209

energy was 35 eV. A separate injection was needed for each analyte, implying that six injections for analysis of PCDD/F, PCBs, PCDEs, PBDD/Fs, PBBs, and PBDEs were necessary for this investigation.

Analytical Stage

The fiber filter and a two-stage cartridge for each exhaust sampling were examined to determine the concentration of the captured pollutants. A Soxhlet extractor was used to extract the exhaust gas samples using *n*-hexane and dichloromethane with a volume ratio of 1:1; each 250 mL was the solvent for 24 hours. To concentrate the extract, the extracts were gently purged with ultrapure nitrogen and later purified using a silica gel column. After obtaining a concentrate of 1 mL, gas chromatography/mass spectrometry (GC/MS) was used for the analysis, and sixteen PAH homologs were detected.

Subsequently, seventeen 2,3,7,8-substituted PCDD/Fs, twelve dioxin-like PCBs, six PCDEs, twelve 2,3,7,8-substituted PBDD/Fs, five PBBs, and fourteen PBDE homologs were analyzed. This stage of the analysis involved treatment of the solution using concentrated sulfuric acid, after which it was subjected to a series of sample purification and fractionation steps including a silica multilayer column, an alumina column, and a column of activated carbon. In the section with the alumina column, elution of the non-planar PCBs and PBBs was carried out with 15 mL of hexane, and then further elution using 25 mL of a 1:24 mixture of DCM and hexane was completed before progressing to the activated carbon column. For the activated carbon column, elution was done using 5 mL of a toluene, methanol, ethyl acetate, and hexane mixture in a volume ratio of 1:1:2:16 to obtain PCDEs, PBDEs, planar PCBs, and PBBs, and then 40 mL of toluene was added. The analytical procedures are described in more detail in a previous work.

RESULTS AND DISCUSSION

Conventional “Criteria” Air Pollutants (CO, CO₂, PM, and NO_x)

At an EGR ratio of 0%, the PM and NO_x concentrations in the exhaust from the diesel engine fueled with B2 were

70.6 mg Nm⁻³ and 352 ppm, respectively. With the power output as the basis of comparison for the pollutants, the emission factors of CO, CO₂, NO_x, and PM were 3.71 g kW-h⁻¹, 872 g kW-h⁻¹, 6.53 g kW-h⁻¹, and 0.38 g kW-h⁻¹, respectively. When the EGR ratio was increased to 5%, the CO, CO₂, NO_x, and PM emission factors were 6.16 g kW-h⁻¹, 850 g kW-h⁻¹, 2.98 g kW-h⁻¹, and 0.61 g kW-h⁻¹, respectively. The results indicate that the NO_x emissions from the engine decreased by 54.4% and the CO₂ emission factors dropped by 2.5% for the 5% increase in the EGR rate. However, for the other two pollutants, the rate of emissions increased with an increase in the EGR ratio, and the CO and PM produced by the engine increased by 66%, and 60.5%, respectively. The experimental data shows that increasing the EGR only significantly decreased NO_x emissions, while CO and PM exhibited a significant increase. Therefore, the EGR ratio should not be increased blindly. As an alternative, caution should be exercised in order to strike a balance in the trade-off between PM and NO_x emissions and hence minimize the overall pollution effects. Similar findings have been reported by Sunil Naik and Balakrishna (2018), who conducted experiments with B10 and B20 fuels at EGR rates of 0%, 10%, and 20%. The average NO_x emission reduction rates of the B10 and B20 test fuels at EGR rates of 0%, 10%, and 20% were approximately 18.24%, 17.67%, and 17.14%, respectively. However, CO in the exhaust increased significantly as the proportion of the exhaust gas recirculation rate increased.

POPs Emitted from a Diesel Engine Running on B2 Biodiesel

The mass concentrations of pollutants in the exhaust gases using B2 fuel (98% fossil-based diesel and 2% biodiesel) in a diesel engine are in Table 3. Their toxic equivalency factors (TEFs), which are parameters used to calculate the toxicity of POPs, were applied in the calculation of their respective equivalent toxicities (Van den Berg *et al.*, 1998). The TEFs for PBBs, PBDEs, and PCDEs are not widely accepted yet and as such are only evaluated on the basis of mass concentration (Tsai *et al.*, 2018). The results of the analysis for each persistent organic pollutant using the two EGR ratios are discussed below.

Table 3. Concentrations of particulate matter, NO_x and POPs in the emissions from a diesel engine using B2 as the fuel.

Pollutants		Concentration
PM	mg Nm ⁻³	70.6
NO _x	ppm	352
PAHs	mass concentration (μg Nm ⁻³) Total-BaP _{eq} (μg Nm ⁻³)	9.73 0.0449
PCDD/Fs	mass concentration (pg Nm ⁻³) I-TEQ (pg I-TEQ Nm ⁻³)	39.6 2.54
PCBs	mass concentration (pg Nm ⁻³) WHO-TEQ (pg WHO-TEQ Nm ⁻³)	10.7 0.0339
PCDEs	mass concentration (pg Nm ⁻³)	ND
PBDD/Fs	mass (pg Nm ⁻³) TEQ (pg TEQ Nm ⁻³)	227 0.665
PBBs	mass concentration (pg Nm ⁻³)	236
PBDEs	mass concentration (ng Nm ⁻³)	98.1

PAH Emission Factors

Without EGR, the emission factor for PAHs based on mass concentration was $107 \mu\text{g kW}^{-1}$, while on the basis of toxic equivalency was $0.488 \mu\text{g BaPeq kW}^{-1}$. After applying an EGR ratio of 5%, the total mass emission factor for the PAHs increased by 9.07 times, while the toxic equivalency factor increased by 3.97 times, as shown in Table 4. It can be seen from the characteristic profile presented in Fig. 1 that the species of polyaromatic hydrocarbons with higher molecular weight increased significantly, indicating that there was incomplete combustion at the 5% EGR ratio (Zhang *et al.*, 2013). Specifically, there was a decrease in naphthalene, acenaphthylene, and acenaphthene, while an increase was observed for fluorene, phenanthrene, anthracene, fluoranthene, and pyrene. The highest increase by about $10 \mu\text{g BaPeq kW}^{-1}$ was observed for phenanthrene. The percentage contribution of the remaining PAHs were negligible for both EGR ratios (Aliksson and Denbratt, 2006; Borillo *et al.*, 2018).

Concentration of PCDD/Fs in the Emissions

According to previous literature, PCDFs can be formed by a condensation reaction of chlorophenol with chlorobenzene via PCDEs (Liu *et al.*, 2008). In addition, PCDEs can

generate PCDD/Fs through a pyrolysis reaction. Therefore, PCDEs may be important precursors for the formation of PCDD/Fs. Consequently, the concentration of PCDEs is significantly lower than the concentration of PCDD/Fs in diesel engine exhaust. A similar phenomenon has been reported in a study of simulated fly ash in a flow reactor system (Liu *et al.*, 2011). One explanation for this phenomenon is the formation of a common precursor of PCDEs and PCDD/Fs such as chlorobenzene and chlorophenol, as well as surface competition. Another explanation is that PCDEs are mostly converted to PCDD/Fs as intermediates during the reaction. From Table 3, the mass concentration of PCDD/Fs was $39.6 \mu\text{g Nm}^{-3}$, with a toxicity equivalence of $2.54 \mu\text{g I-TEQ Nm}^{-3}$.

From Table 4, it can be seen that there is a decrease in PCDD/F emission factors after using the 5% EGR as compared to an EGR ratio of 0%. The possible reason is that when the EGR ratio was 0%, the higher oxygen concentrations in the supplied air for combustion led to the formation of PCDD/Fs through de novo synthesis reactions (Chang *et al.*, 2000).

From the congener profile presented in Fig. 2, it can be observed that except for OCDD and OCDF, the rest of the congeners had a contribution of less than below 10%. The

Table 4. Emission factors of the toxic organic pollutants in EGR exhaust gas from diesel engine flue gas.

		EGR		
		0%	5%	(Emissions at 5% EGR)/ (Emissions at 0% EGR)
PAHs	mass ($\mu\text{g kW}^{-1}$)	107	971	9.07
	Total-BaPeq ($\mu\text{g kW}^{-1}$)	0.488	1.78	3.97
PCDD/Fs	mass ($\mu\text{g kW}^{-1}$)	436	215	0.49
	Total TEQ ($\mu\text{g I-TEQ kW}^{-1}$)	27.5	22.5	0.82
PCB	mass ($\mu\text{g kW}^{-1}$)	107	1536	14.36
	Total TEQ ($\mu\text{g WHO-TEQ kW}^{-1}$)	0.368	1.77	4.81

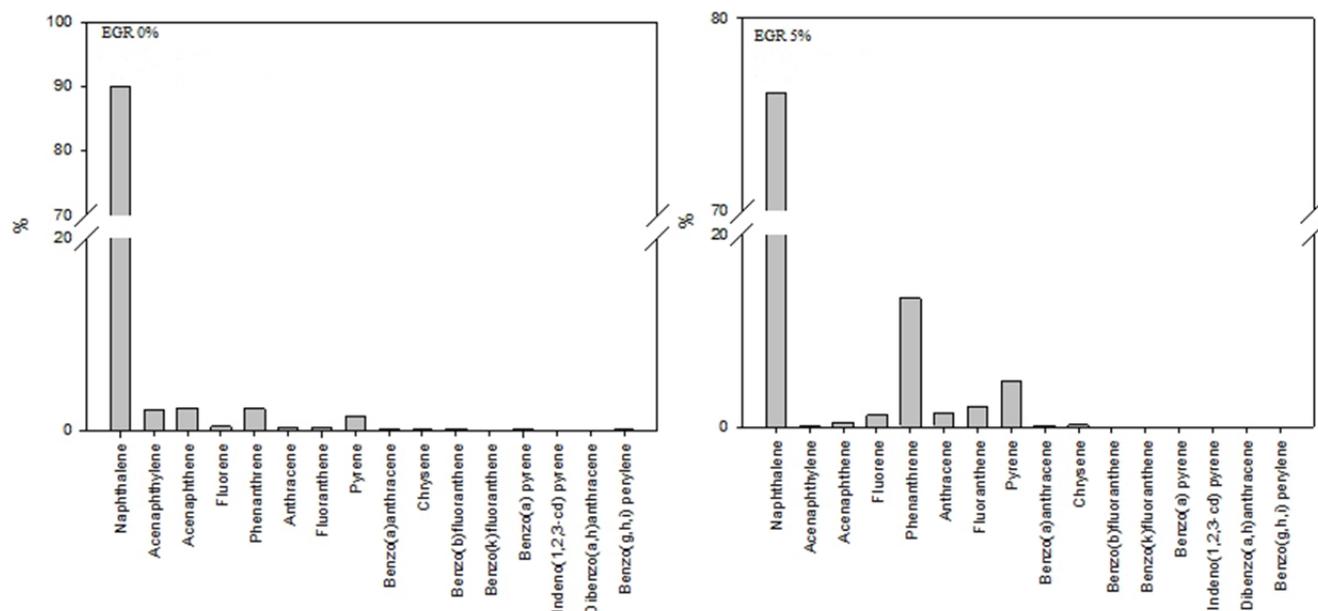


Fig. 1. PAH profiles using 0% and 5% EGR.

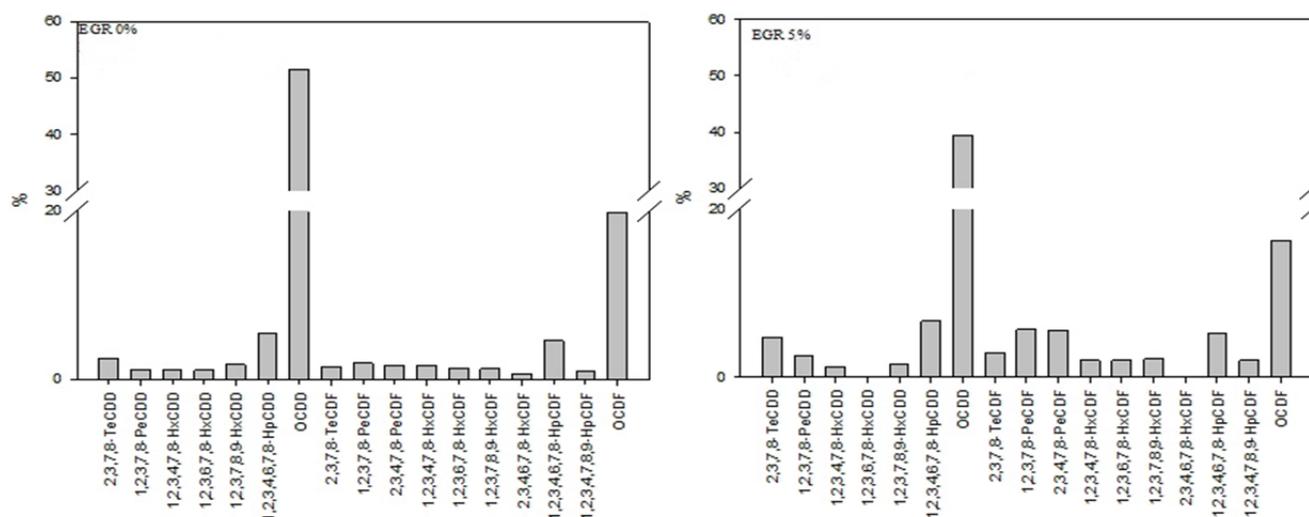


Fig. 2. PCDD/F congener profiles using 0% and 5% EGR.

contribution of OCDD and OCDF was 50% and 20%, at 0%-EGR and 40% and 18% at 5%-EGR respectively. There was an increase in the percentage of contribution in the following congeners: 2,3,7,8 TeCDD; 1,2,3,7,8 PeCDD; 2,3,7,8 TeCDF; 1,2,3,7,8 PeCDF; 2,3,4,7,8 PeCDF; 1,2,3,6,7,8 HxCDF; 1,2,3,7,8,9 HxCDF; and 1,2,3,4,7,8,9 HpCDF. However, a slight decrease was observed for the percentage contribution of 1,2,3,6,7,8 HxCDD; 1,2,3,7,8,9 HxCDD; and 2,3,4,6,7,8 HxCDF. The change in the toxicity of the following congeners was insignificant: 1,2,3,4,7,8 HxCDD; 1,2,3,4,6,7,8 HpCDD; 1,2,3,4,7,8 HxCDF; and 1,2,3,4,6,7,8 HpCDF. Overall, the toxic equivalency decreased, implying that increasing the EGR ratio to 5% will result in lower emission toxicity (Cheruiyot *et al.*, 2017).

Concentration of PCBs in the Emissions

PCBs had a concentration of 10.7 pg Nm^{-3} and a toxic equivalency of $0.0339 \text{ pg WHO}_{2005}\text{-TEQ Nm}^{-3}$, as shown in Table 3. After applying an EGR ratio of 5%, the mass emission factor of PCBs was 14.4 times higher than the original value at 0% EGR, while on the basis of toxicity, it increased by 5 times, as shown in Table 4. The increase in both mass concentration and toxic equivalency can be attributed to incomplete combustion as a result of increasing the EGR ratio (Hedman *et al.*, 2006).

CONCLUSION

An increase in EGR from 0% to 5% is a viable NO_x control technology since it reduced NO_x emission factor by 54.4%. However, it also increased the PM emission factor by 60.5% and as such should be combined with additional aftertreatment, for instance, diesel particle filters (DPF) to achieve simultaneous reductions in both NO_x and PM. Raising the EGR reduced the combustion efficiency hence increasing the emission factors of PAHs and PCBs by 9.07 times and 14.36 times on the basis of mass and 3.97 times and 4.81 times based on the toxicity. Further investigations are therefore necessary in the development of more

sustainable ways to reduce organic toxic pollutants from diesel engines.

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