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Effect of Exhaust Gas Recirculation on CO Emissions from A Turbocharged Diesel Engine

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Abstract: In this paper an experimental investigation was conducted to study the effect of using different ratios of Exhaust Gas Recirculation (EGR) on the emissions of Carbon Monoxide (CO) from a turbocharged diesel engine. Tests were carried at different engine speeds, brake power and EGR ratios. The experimental results obtained showed that the emissions of carbon monoxide are significantly affected by changes in engine speed, EGR ratio and Brake Power. As a result a simple quantitative correlation which relates CO emissions to engine speed, EGR ratio and brake power is presented. A reasonable agreement was shown when the measured experimental and predicted results are compared.

Keywords: *Internal Combustion Engines; Emissions; Carbon Monoxides; EGR.*

1. INTRODUCTION

Exhaust gas recirculation (EGR) is used to reduce nitrogen oxides (NO_X) emissions in petrol and diesel engines [1]. EGR works by recirculating a portion of an engine's exhaust gas back to the engine cylinders. In a petrol engine, this inert exhaust displaces the amount of combustible matter in the cylinder [2]. In a diesel engine, the exhaust gas replaces some of the excess oxygen in the pre-combustion mixture. Because NO_X forms primarily when a mixture of nitrogen and oxygen is subjected to high temperatures. The lower combustion chamber temperatures caused by EGR reduces the formation of NO_X emissions [3]. Most modern engines now require exhaust gas recirculation to meet emissions standards [4].

The largest part of most combustion gas is nitrogen (N_2), water vapor (H_2O), and carbon dioxide (CO_2) which are not toxic or noxious (although carbon dioxide is generally recognized as a greenhouse gas that contributes to global warming). A relatively small part of combustion gas contains undesirable noxious or toxic substances, such as carbon monoxide (CO) from incomplete combustion, hydrocarbons from unburnt fuel, nitrogen oxides (NO_X) formed during excessive combustion temperatures, and particulate matter (PM) [5].

Carbon monoxide (CO) is a colorless, odorless, and tasteless gas that is slightly lighter than air. It is toxic to humans and animals when encountered in higher concentrations, although it is also produced in normal animal metabolism in low quantities. In the atmosphere it is spatially variable, short lived, having a role in the formation of ground-level ozone [6]. Carbon monoxide consists of one carbon atom and one oxygen atom and is produced from the partial oxidation of carbon-containing compounds. It is formed when there is not enough oxygen to produce carbon dioxide (CO_2), such as when operating a stove or an internal combustion engine in an enclosed space. In the presence of oxygen, carbon monoxide burns with a blue flame, producing carbon dioxide [7].

Carbon monoxide is absorbed via the lungs into the bloodstream, where it replaces oxygen by attaching chemically to hemoglobin forming carboxyhaemoglobin. This reduces the oxygen carrying capacity of the blood. In addition the dissociation of oxyheamoglobin is also affected so that the supply of oxygen to tissues is further reduced [8].

Higher amount of smoke in the exhaust is observed when the engine is operated with EGR compared to without EGR. Smoke emission increases with increasing engine load and EGR rates.EGR reduces availability of oxygen for combustion of fuel, which results in relatively incomplete combustion and increased formation of PM and reducing NO_X emissions from diesel engine [9].

It is obvious that the brake torque decreases as the EGR rate increases. This is largely due to the fact that as EGR rate is increased, the concentration of air in the cylinder decreases and consequently it reduces the brake torque [10]. The highest value of brake torque is presented at stoichiometric mixture (λ

= 1.0) when compared to the other mixtures. The reason being that at stoichiometric mixture, there is efficient combustion; all the air provided is effectively utilized for combustion process [11].

Increasing engine speed at a constant EGR rate leads to increase in CO and unburned hydrocarbons (UHC) emissions due to the incomplete combustion caused by shorter combustion duration and less homogeneous mixture. Also increasing EGR reduces the amount of oxygen and leads to incomplete combustion and therefore increases CO emission due to lower combustion temperature. HC emission also increases as a result of lower combustion temperatures [12].

However the effect of introducing EGR on performance, combustion and emissions production at different engine speeds are easy to depict. With the increase of EGR ratio, the brake power and NO_X decreased while the emissions of carbon monoxide increased. Therefore, the optimum EGR rate should be carefully determined in order to obtain the better engine performance and optimum emissions. EGR flow should match the following operating conditions to obtain good engine performance and meet the diesel engine NO_X emissions regulations:

However, as the EGR flow rate at a given engine operating condition increases, the combustion instability increases. The combustion instability increases cyclic variations resulting in the deterioration of engine performance and emissions [13].

2. MATERIALS AND METHODS

The experimental results in this paper were obtained from a turbocharged four - cylinder diesel engine (2.5 litres) four-stroke direct-injection having a rated power of about 78kW at 4200rpm (bore 91.1mm, stroke 95mm, and compression ratio 21:1).

A hydraulic dynamometer type (HPA - Test) was used to load the engine at different engine speeds. It consists of an absorption (or absorber/driver) unit, and usually includes means for measuring torque and rotational speed. An absorption unit consists of some type of rotor in housing. The rotor is coupled to the engine under test and is free to rotate at whatever speed is required for the test. An absorbing dynamometer acts as a load that is driven by the prime mover that is under test. Power Absorption Unit is configured to provide the braking force torque load, while the prime mover is configured to operate at whatever throttle opening.

Exhaust gas analyzer type GreenLine 8000 was used in this research. The gas analyzer consists of two main parts the gas analysis Main Control Unit (MCU) and the Remote Control Unit (RCU). The MCU is complete flue gas laboratory and RCU was used to display the measured data. The gas analyzer uses electrochemical cells with two electrodes and electrolyte solution to measure NO_X emissions. The gas analyzer also measured other toxic gases such as CO and SO_2 emissions concentration.

In this paper the EGR valve was required to operate manually. The geometrical dimensions of the EGR valve are 12mm inlet diameter and 7mm for the stroke of the EGR poppet valve as shown in Fig. 1. The diameter of the inlet manifold (flow of the fresh air) was found to be 60mm, therefore the flow area of the EGR related to the intake manifold area is 0.20 (12mm/60mm). The engine is made to run at different EGR ratios (0%, 5%, 10%, 15%) controlled by valve opening percentages (0%, 25%, 50%, and75%) respectively. Table 1 illustrates the relations between EGR valve open percentages and EGR ratio.

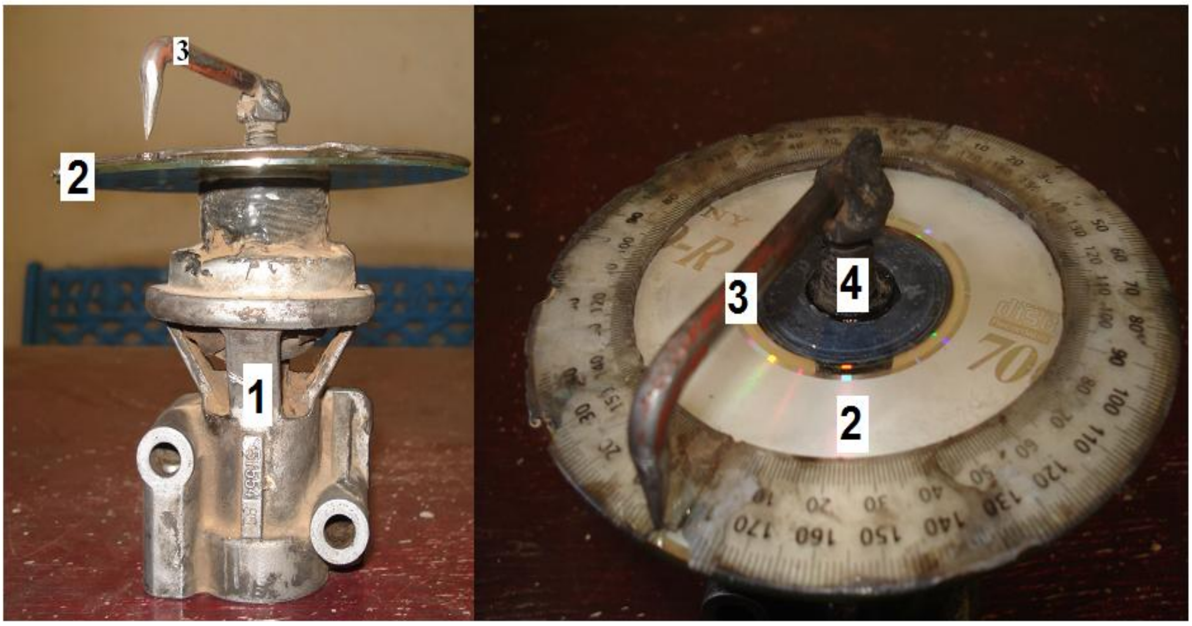

Fig. 1. EGR valve. 1- EGR valve. 2 – 360deg. Protractor. 3 – Pointer. 4- Rotating bolt

Table 1. Relations between EGR valve open percentages and EGR ratio.

No.	EGR valve opening percentage	EGR Ratio	Equivalent Degrees
1	0%	0.00	000.0^{o}
2	25 %	5 %	327.5^{o}
3	50 %	10 %	6550^{o}
4	75%	15%	982.5^{o}
5	100%	20%	1310^{o}

The tests are carried out at the following operating conditions:-

- At different engine speeds (1000, 1500, 2000, and 2500 rpm)
- At different EGR ratios (0, 5, 10, 15, and 20%).
- At different brake powers.

3. RESULTS AND DISCUSSION

All data required to conduct this study are obtained experimentally. Table 2 and Fig. 2 show the impact of CO emissions from TC diesel engine when EGR system is used at different ratios. The amount of carbon monoxide emitted from the engine increase, as the EGR ratio increase. This is because the EGR consists of carbon dioxide, carbon monoxide and water vapor. Secondly as the engine speed increases the potential of incomplete combustion will occur, because the time per stroke is shorter, and this in turn is found to increase the emissions of carbon monoxide significantly.

The increase in CO emissions depends on EGR ratio. As the EGR ratio increases the emission of CO is found to increase when compared to the emissions of the TC engine. The last results show that, the EGR ratios are found to reduce the amount of oxygen entering the combustion chamber, and led to incomplete combustion, and hence the CO emissions increased due to the lower combustion temperatures. HC emissions also increased as a result of reducing air flow rate. A rich mixture occurred due to less amount of air, thus hydrocarbon emissions are released in the exhaust.

On the other hand, as the engine speed increases, the emissions of CO increased. At the set-up of TC + 15% EGR and at 1000, 1500, 2000, and 2500rpm, the CO emissions are equal to 80, 145, 189, and 212 ppm respectively. The above results illustrate that increasing engine speed at a constant EGR rate tend to increase the CO emissions, due to the incomplete combustion caused by the shorter combustion duration and less homogeneous mixture. Increasing EGR dilutes the intake charge resulting in decreasing the combustion temperature and leads to incomplete combustion and therefore the CO emissions will be increased.

Table 2. The experimental data

Test set-up	N (rpm)	BP (kW)	CO (ppm)	Brake Specific CO	Log (CO)		Error
				(ppm . kW^{-1})	Measured	Calculated	(%)
TC Engine	1000	5.760	18	3.13	1.255	1.397	11.26
	1500	11.78	52	4.42	1.716	1.628	-5.13
	2000	17.80	80	4.49	1.903	1.814	-4.66
	2500	23.55	92	3.91	1.964	1.969	0.26
TC+ 5% EGR	1000	5.110	48	10.4	1.681	1.769	5.22
	1500	10.78	103	9.56	2.013	1.993	-0.97
	2000	16.75	140	8.36	2.146	2.174	1.28
	2500	22.51	160	7.46	2.204	2.325	5.46
TC+10% EGR	1000	3.370	60	17.81	1.778	1.867	5.01
	1500	8.870	122	14.32	2.086	2.042	-2.13
	2000	14.66	165	11.26	2.217	2.209	-0.40
	2500	20.66	185	9.44	2.267	2.349	3.60
TC+15% EGR	1000	2.620	80	30.55	1.903	1.927	1.24
	1500	8.350	145	17.97	2.161	2.059	-4.76
	2000	14.08	189	13.42	2.276	2.221	-2.46
	2500	19.26	212	11.32	2.326	2.368	1.77
TC+20% EGR	1000	2.020	104	51.46	2.017	1.987	-1.48
	1500	7.700	175	23.64	2.243	2.079	-7.32
	2000	13.37	220	16.83	2.342	2.234	-4.62
	2500	18.75	244	13.60	2.387	2.376	-0.49

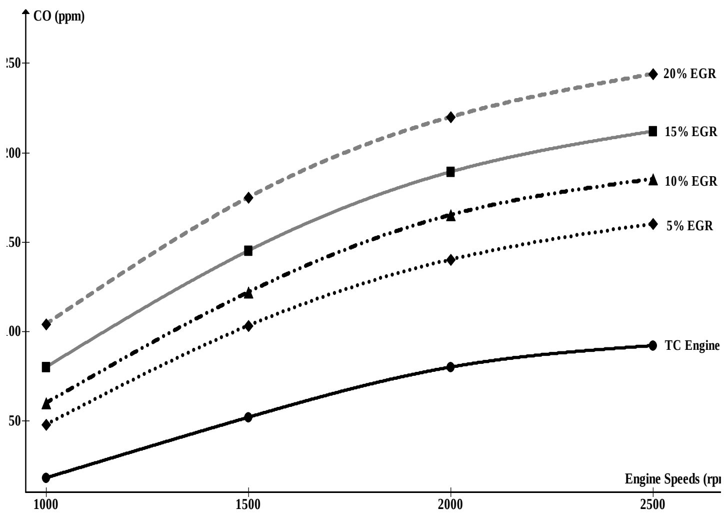

Fig. 2. Impact of EGR systems on CO emissions

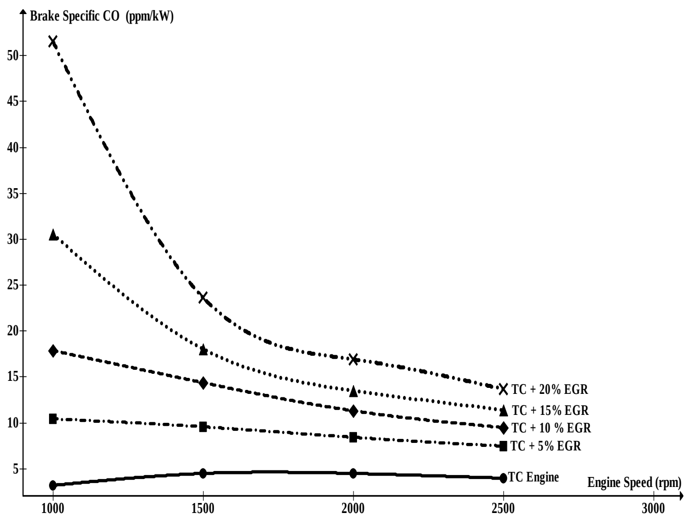

Fig. 3. Impact of Engine Speed on Brake Specific CO at different EGR ratio

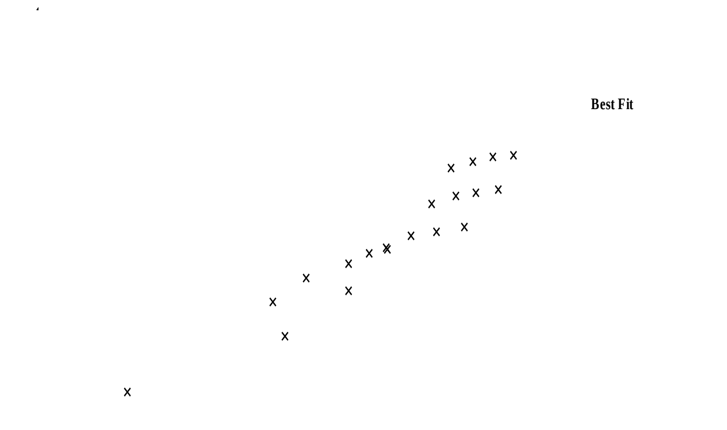

Fig. 4. Calculated CO emissions versus measured

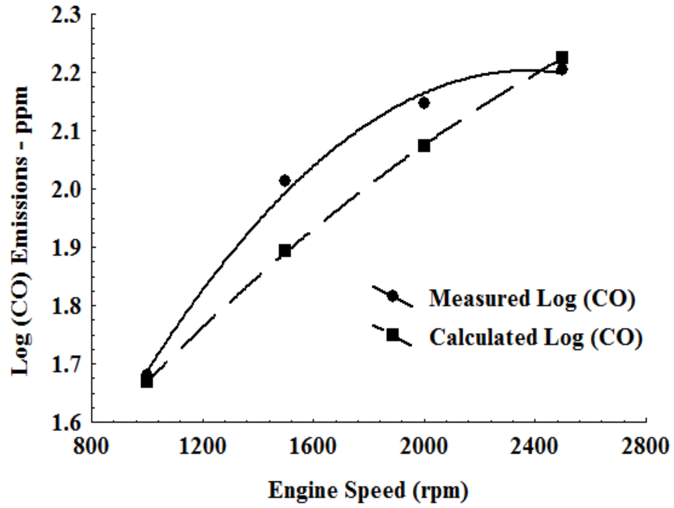

Fig. 5. Measured and calculated CO versus engine speed at 5% EGR.

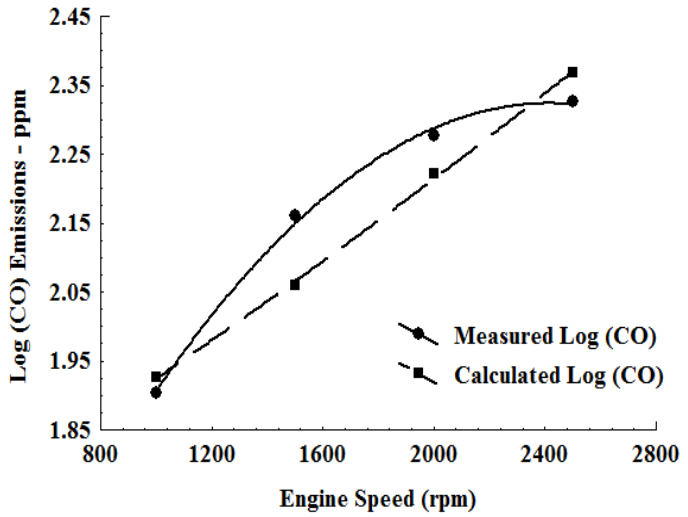

Fig. 6. Measured and calculated CO versus engine speed at 15% EGR

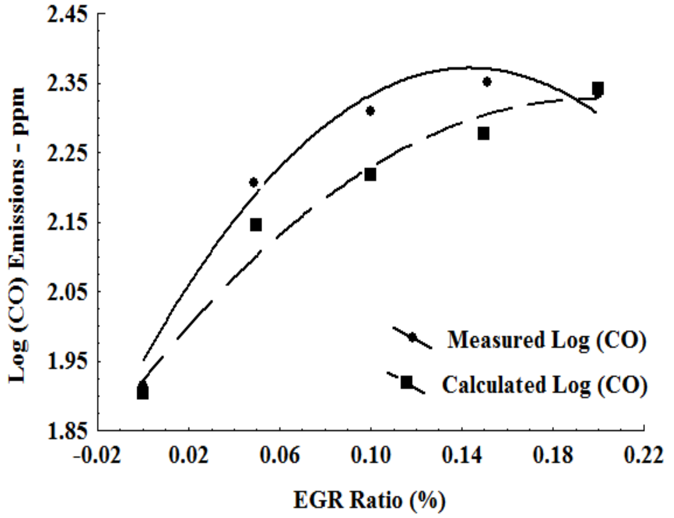

Fig. 7. Measured and calculated CO versus EGR ratios at 2000rpm

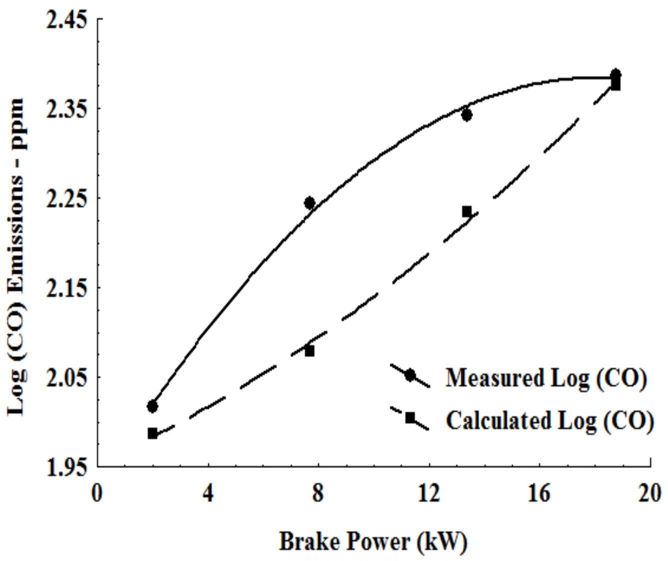

Fig. 8. Measured and calculated CO versus Brake Power at 20% EGR

Brake specific carbon monoxide (bsCO) is a ratio between the emissions of carbon monoxide CO (in ppm) and the brake power (in kW). Fig. 5 shows the variation of bsCO ratio at different EGR rates for different speeds. It is obvious that the bsCO increases as EGR rate increases i.e., CO concentration is increasing with increasing of EGR rates. This is because as the EGR rate is increased, the burning velocity and combustion maximum temperature will reduce due to the dilution effect of EGR and also decrease the cylinder gas temperature. However, the decrease in cylinder gas temperature during combustion process eventually results in increasing the CO concentration. Further excess air will remarkably increase the cylinder gas temperature and decrease the emissions of CO. On the other hand increasing both the engine speed and EGR ratio increased the emissions of CO.

With reference to Table 1 at 2000rpm and TC engine, the bsCO is equal to 4.49 ppm/kW. When introducing EGR in ratios of (5%, 10%, 15%, and 20%) the bsCO are found to be equal to 8.36, 11.26, 13.42, and 16.83 ppm/kW respectively. The increase of bsCO is due to the reduction in brake power and the increase in the emissions of CO as a result of adding EGR. In the presence of EGR the bsCO decreased as the engine speed increased. This is because as the engine speed increased the brake power will increase, and as a result the bsCO will tend to decrease. At low engine speeds, EGR caused a reduction in the engine brake power significantly, which led to a remarkable increase in the brake spesific carbon monoxide.

3.1 Data Correlation

A simple correlation for emissions of CO from TC diesel engine has been developed. The effects of different engine operating parameters on emissions quantity have been investigated experimentally. The experimental results showed that the CO emissions are significantly affected by changes in engine speed (N), EGR ratio, and brake power (BP). As a result a simple quantitative formula which relates CO emissions to these variables is presented. From the experimental results CO emissions are found to be best represented to the above variables by the following relationship:

$$log(CO) = 65.505 \times N^{0.0134} - 0.224 \times Ln(BP) + 0.334 \times EGR^{0.021} - 70.069 \qquad (1)$$

Table 2 illustrates comparison between measured and calculated CO. The calculated CO emissions were calculated by using formula (1) above. Comparisons are made at different engine speeds, brake power and EGR ratios. Good agreement is obtained (average error ranged between +11 and - 6%) when comparisons are carried out between calculated and measured emissions as shown in Fig. 4.
Figs 5 to 8 show a comparison between measured and calculated emissions of carbon monoxide. The comparison based on different engine speeds and variable ratios of EGR and brake power.

4. CONCLUSIONS

It may be concluded that the emissions of carbon monoxide CO increased in the presence of EGR system. EGR was found to lower the combustion temperature which in turn leads to a reduction in the effectiveness of combustion and a significant increase in carbon monoxide emissions. The correlation presented in this paper is useful to predict the CO emissions related to the engine speed, brake power, and EGR ratio. Good agreement was shown when the predicted CO emissions are compared to those found experimentally at different conditions.

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