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Prediction of Nitrogen Oxides Emissions in a Turbo-charged Diesel Engine with Water Injection System

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Abstract: This paper presents an empirical correlation deduced to predict Nitrogen Oxides (NO_X) emissions form a turbocharged diesel engine (TC engine) when using inlet manifold water injection as a suppressant NO_X emissions. NO_X emissions are determined as a function of different engine operating parameters such as engine speed, brake power, and the rate of injected water that are measured during the experiments. The experimental results showed that NO_X emissions are significantly affected by changes in engine speed, brake power and rate of injected water. The NO_X model presented in this paper can be used as a research tool, particularly in studying the way in which diesel engine design influences exhaust emissions.

Keywords: *Internal Combustion Engines; Emissions; Nitrogen Oxides.*

1. INTRODUCTION

NO_X is a collective name given to the oxides of nitrogen. These being Nitric Oxide (NO), Nitrogen Dioxide (NO_2) and Nitrous Oxide (N_2O). In general NO, is emitted from fossil fuel combustion in the form of NO, where upon it is oxidized to NO_2 in the atmosphere, although certain conditions favour the production of NO_2 and N_2O leading to significant emissions [1]. They are produced from the reaction of nitrogen and oxygen gases in the air during combustion, especially at high temperatures. In areas of high motor vehicle traffic, such as large cities, the amount of nitrogen oxides emitted into the atmosphere as air pollution can be significant. NO_X gases are formed everywhere where there is combustion like in an engine. In atmospheric chemistry, the term means the total concentration of NO and NO_2. NO_X react to form smog and acid rain. NOX are also central to the formation of tropospheric ozone [2].

In internal combustion engines, water injection sprays water into the cylinder or incoming air to cool the combustion chambers of the engine. Which increases the charge density and hence the amount of air that enters the cylinder. An additional effect comes later during combustion when the water absorbs large amounts of heat as it vaporizes reducing peak temperature and resultant NO_X formation [3].
Emission models have been developed for diesel-powered vehicles. Ramamurthy *et al*. [4] fit a polynomial curve to nitrogen oxides (NO_X) emissions based on power of a heavy-duty diesel vehicle and described the simple correlation as near-linear. Cooper and Andreasson [5] used non-linear regression to predict NO_x emissions of a diesel powered passenger ferry. Although fuel rate, engine load, ambient air temperature, relative humidity, barometric pressure, charge air temperature, exhaust temperature and oxygen (O_2) concentration in the exhaust were initially measured. The selected model used only oxygen (O_2) concentration in the exhaust and engine power [5].

Yanowitz *et al*. [6] used test data from a heavy-duty vehicle transient test to predict diesel emissions based on engine power. They found a good linear correlation between the rates of horsepower increase and particulate matter emissions. Krijnsen et al. [7] used inputs of engine speed, injection pump rack position, charge air pressure and charge air temperature to successfully model NO_X emissions from a diesel engine. They used an artificial neural net, a split and fit algorithm, and a nonlinear polynomial model. Results indicated that the NO_X predictions based on these algorithms were more accurate than a linear model.

Pawar *et al*. [8] studied a numerical method to predict the NO_X emissions by considering the parameter equivalence ratio. The study showed that whilst equivalence ratio increases, the NO_x increases. Maass *et al*. [9] built a parallel network structure consisted of three non-linear autoregressive exogenous inputs to predict smoke emissions of the diesel engine. Ghobadian [10] analyzed the diesel engine performance and exhaust emission analysis using waste cooking biodiesel fuel with an artificial neural network (ANN) and can predict the engine performance and exhaust emissions. Sayin *et al*. [11] compared the experimental results of performance and exhaust emissions of a gasoline engine using the (ANN).

Kiani *et al*. [12] predicted the performance and exhaust emissions in Spark-Ignition engine fueled with ethanol-gasoline blends with the application of artificial neural network. Hashemi *et al*. [13] studied in diesel engine and predict NO_X, CO, CO_2 and HC emissions by means of back propagation (BP). Obodeh *et al*. [14] predict NO, power and sfc (specific fuel consumption), fueled with diesel in diesel engine using ANN BP algorithm.

2. TEST PROCEDURE

A 4D56 turbocharged four-cylinder diesel engine (2476 cc) was used for the emissions tests. The rated power is 78kW at 4200rpm (bore 91.1mm, stroke 95mm, and compression ratio 21:1). A hydraulic dynamometer type (HPA - Test) was used to provide the engine load and measure its speed. An exhaust gas analyzer type GreenLine 8000 was used in this research. The gas analyzer uses electrochemical cells with two electrodes and electrolyte solution to measure NO_X emissions. The gas analyzer also measures other toxic gases such as CO and SO_2 emissions concentration. Water injection system was built locally to provide different rates of injected water by using variable feeding pressures (5 and 10bar) and different nozzle diameters (0.1, 0.3, and 0.5mm). Table (1) shows the water mass flow rate of water injection system at each operating condition, where the injected water rate was measured experimentally. When the water passes through the nozzle, a process known as flash evaporation occurs which effectively vaporizes the water in the engine charge.

The TC engine was operated with water injection systems at different rates as shown in table (1). Four engine speeds were considered (1000, 1500, 2000, and 2500rpm) for each rate of injected water. Brake power was calculated from the measured engine speed (rpm) and torque (Nm). NO_X emissions were measured using the gas analyzer.

The Statistical Package for the Social Sciences (SPSS) as a predictive analytics software was used in this study to design a model to predict NO_X emissions related to engine speed, brake power and rate of injected water.

3. RESULTS AND DISCUSSION

All data required to conduct this study are obtained experimentally. The brake power was calculated by using the equation (1).

$$\text{Brake Power (BP)} = 2\pi NT \qquad (1)$$

where

N = Engine speed in revolution per second (rps).

T = Engine output torque (Nm).

A simple correlation for predicting NO_X emissions 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 NO_X emissions are significantly affected by changes in engine speed, water injection rate, and brake power. As a result, a simple quantitative formula which relates NO_X emissions to these variables is presented. From the experimental results NO_X emissions are found to be best representing the above variables by the following relationship:

$$\ln (NO_X) = 1.375 \times \log (N) - 209.03 \times \exp (WI) + 0.012 \times BP \; 0.782 + 217.69 \qquad (2)$$

Table (2) shows a comparison between measured and calculated NO_X. The calculated NO_X was obtained by using the equation (2). Comparison is carried out at different engine parameters such as engine speed, engine brake power and WI. Reasonable good agreement is obtained (average error ± 9%) when the calculated emissions are compared with those measured as shown in figure (1). The comparison is carried out at different test conditions as in figures 2 – 8.

Table 1. Mass flow rate of WI system

Nozzle Diameter (mm)		Mass flow rate (kg/s)		Mass flow rate (kg/s)
0.1	Pressure 5bar	1.367e-4	Pressure 10bar	2.2e-4
0.3		7.283e-4		9.2e-4
0.5		1.236e-3		1.52e-3

Table 2. Measured and calculated NOX emissions

Speed (rpm)	WI (kg/s)	BP (kW)	NOx (ppm) Measured	NOx (ppm) Calculated	Error (%)
1000	0.000137	5.1	92	95	-3
1500	0.000137	13.35	85	78	8
2000	0.000137	19.9	68	68	0
2500	0.000137	26.17	60	61	-2
1000	0.000220	4.58	86	93	-2
1500	0.000220	13.62	81	77	5
2000	0.000220	20.21	65	67	-3
2500	0.000220	26.8	57	61	-6
1000	0.000728	4.1	80	83	-4
1500	0.000728	14.13	77	69	10
2000	0.000728	20.85	62	60	2
2500	0.000728	27.3	54	55	-1
1000	0.000920	3.52	75	80	-6
1500	0.000920	10.38	73	65	11
2000	0.000920	17.8	57	57	0
2500	0.000920	24.86	50	52	-4
1000	0.001236	2.92	70	74	-6
1500	0.001236	9.27	69	61	12
2000	0.001236	15.17	53	53	0
2500	0.001236	20.73	45	48	-6
1000	0.001520	2.36	65	70	-7
1500	0.001520	8.78	65	57	12
2000	0.001520	14.75	49	50	-1
2500	0.001520	20.16	40	45	-12

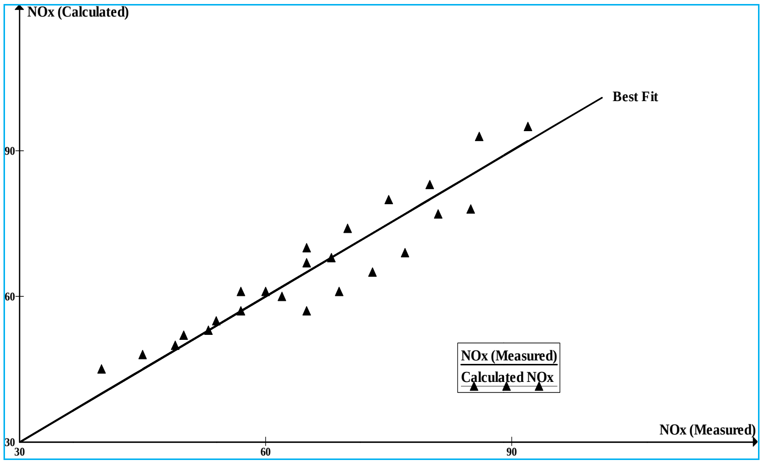

Fig. 1. calculated NO_X emissions versus measured

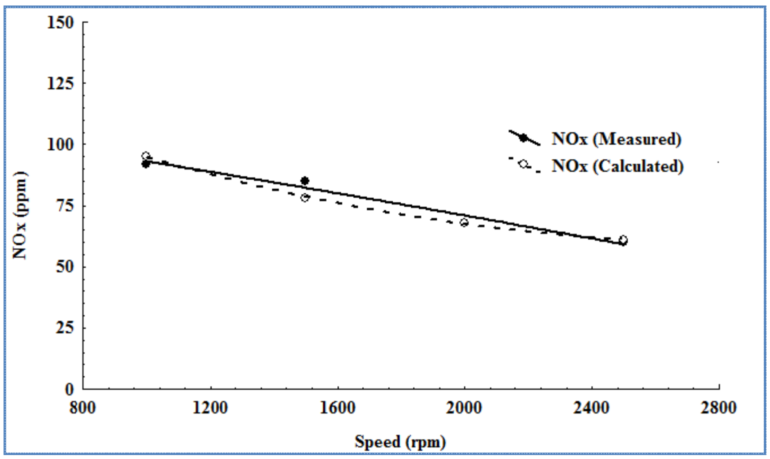

Fig. 2. measured and calculated NO_X versus engine speed at WI setup (0.1mm at 5bar).

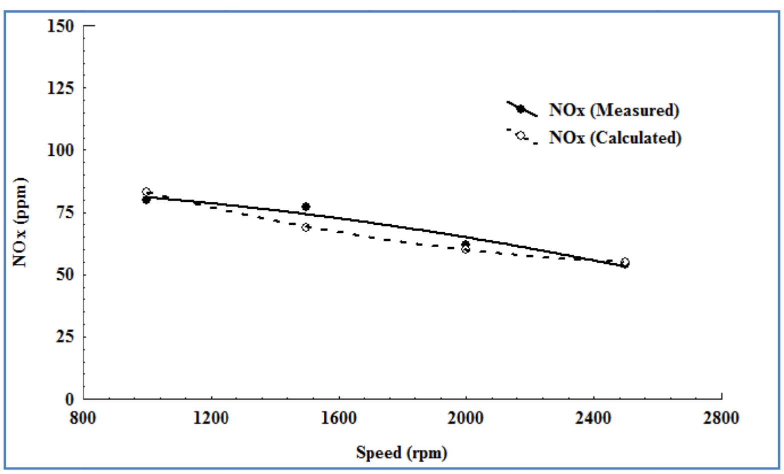

Fig. 3. measured and calculated NO_X versus engine speed at WI setup (0.3mm at 5bar).

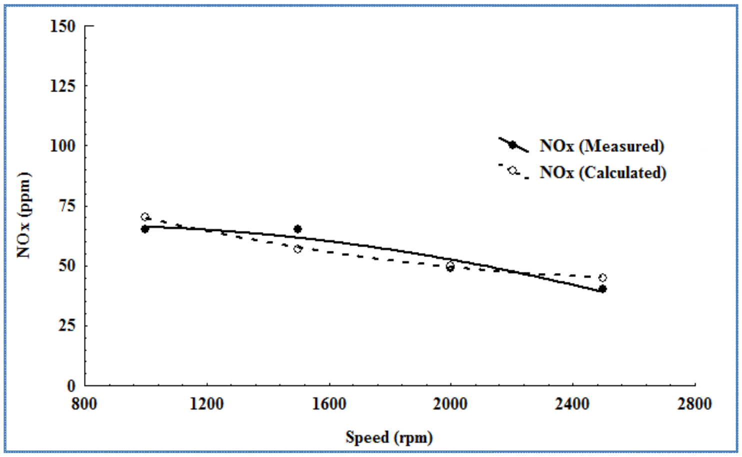

Fig. 4. measured and calculated NO_X versus engine speed at WI setup (0.5mm at 5bar).

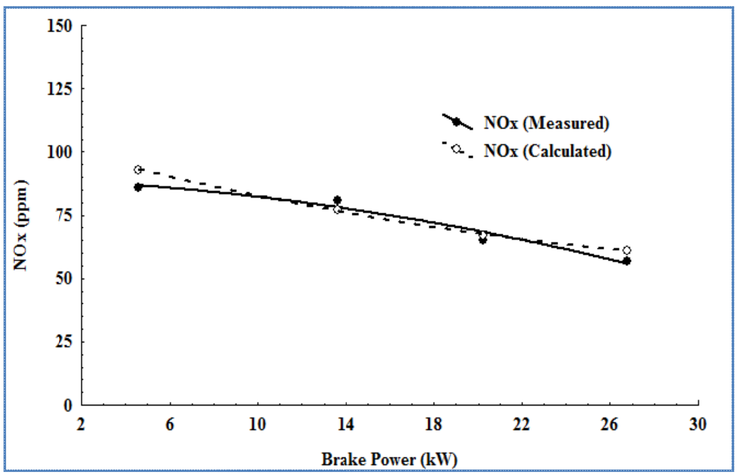

Fig. 5. measured and calculated NO_X versus brake power at WI setup (0.1mm at 10bar).

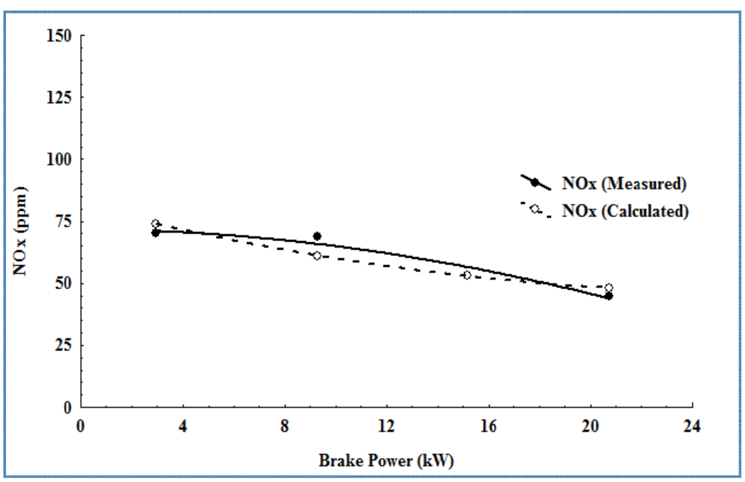

Fig. 6. measured and calculated NO_X versus brake power at WI setup (0.5mm at 5bar).

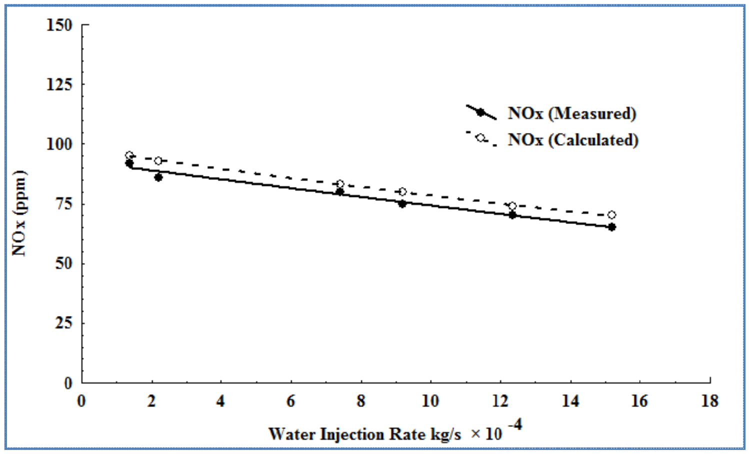

Fig. 7. measured and calculated NO_X versus WI setups at 1000rpm

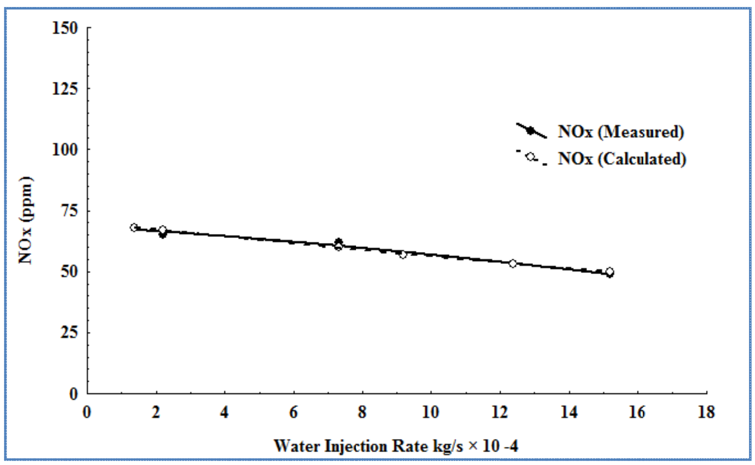

Fig. 8. measured and calculated NO_X versus WI setups at 2000rpm

4. CONCLUSIONS

It may be concluded that the simple NO_X emissions correlation presented in this paper is useful in predicting changes in NO_X emissions in relation to engine operational variables such as engine speed, brake power, and rate of injected water. The correlation could be incorporated into a simulation program to predict the quantity of NO_X emissions of the TC diesel engine employing a water injection system.

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