Study of NO_X Modelling of HCNG engine by applying the Gaussian function

Anas Rao, Roopesh Kumar Mehra, Hao Duan, Fanhua Ma*

Abstract - Addition of hydrogen to the natural-gas increases the NOx emission which is proved by previous researches of HCNG engines. One of the impressing way to predict NOx emission to save the time and cost is the numerical study. This article presents statistical approach of NOx prediction by using curve-fitting. Experiments have been performed on the Dongfeng engine from the air-fuel ratio (1 to 1.8), manifold absolute pressure (50 to 105 kPa) and hydrogen percentage (0 to 30%) at MBT (30° CA) and optimum speed (1200 rpm). The value of NO_x emission has been curve fitted with respect to the air-fuel ratio by Gaussian function. Thereafter, the co-efficient of the function have been curve fitted with respect to the manifold absolute pressure. In the third step, the hydrogen percentage in the compressed natural gas has been introduced in the program for the simulation of NO_x emission. The error correction has been applied for the accurate prediction. The numerical program has been used for the simulation of the NO_x emission and the results have been validated with the experimental results. The confidence (z) of the model is approximately 95% while, the regression line is 93.86% close to the actual values. The high values obtained of confidence and regression line makes this an effective model to be referred by the researchers. It is found quite impressing that the average error of program is +7.55%.

KEYWORDS: Gaussian function, curve fitting, NO_x emission, HCNG engine

1. INTRODUCTION

The hydrogen-enriched compressed natural gas (HCNG) is promising fuel for internal combustion engines in terms of brake thermal efficiency, laminar burning speed and wide range of operating condition. However, the concentration of NO_x emission is significantly higher as compared to the compressed natural gas at a particular air-fuel ratio. Various researchers studied the NO_x emission through experimentation at various operating conditions [1–5] .While, some researchers studied the NO_x emission with the help of numerical simulation by Zeldovich, prompt, N_2O and NNH mechanisms [6–9]. On the other side, the statistical analysis is also an impressive way to study the NOx emission which is useful to get correlation co-efficient.

A number of research scholars have applied the neural network, quadratic polynomial and SVM methods in order to determine the performance and NO_x emission of IC engine. Martinez et al. [10] have applied the Artificial Neural Network (ANN) tool for the prediction of fuel consumption and NO_x emission. They have used MOPO program for tuning of the weights and Fuzzy network as the decision maker. Additionally, they deduced correlation co-efficient for the fuel consumption and NO_x emission which are found to be 0.979 and 0.969 respectively. Kiani et al. [11] have used the ANN model for the prediction of performance and NO_x emission for the ethanol blended gasoline engine. The architecture of the program comprises three input and six output parameters for which three and six neurons consisted in the input and output layers respectively with application of the program Levenberg-Mar-quardt (trainlm) to optimize the weights. The estimated correlation co-efficient of the NO_x emission is found to be 0.71. Cent et al. [12] also applied the ANN technique comprised of one hidden layer having 15 neurons. The inputs layer was applied to evaluate parameters like lower heating value, inlet air temperature, engine speed and torque. The brake thermal efficiency, fuel

Corresponding Author Email address:
mafh@tsinghua.edu.cn
State Key Laboratory, Tsinghua University, Beijing, China.

consumption, exhausts temperature, carbon-monoxide and hydrocarbon are incorporated in the output layer. They have used the LM methods to optimize the weights while back propagation have been applied for the reduction of error. The optimal condition of the HCNG engine is studied by Ma et al. [13] using the combined approach of the genetic algorithm and ANN. They have concluded that the LM is much better than BR program. The input layers comprised of air-fuel ratio, ignition timing and hydrogen fraction. While the output layer has been made to evaluate BSFC, NO_x, CH_4 and CO. They concluded that the air-fuel ratio is most important parameter to evaluate NO_x emission before that ignition timing and hydrogen percentage.

Huang et al. [14] applied the neural network, quadratic polynomial and SVM for the performance and prediction of NO_x emission of HCNG engine. They concluded that the SVM is better program as compared to the others. The input layers comprised of engine speed, ignition timing and manifold absolute pressure while, the torque, NG flow and NO_x emission are the output parameters. The prediction error of NG flow and NO_x emission is about 10% and 30% respectively.

Some researchers have developed the NO_x prediction model based on cylindrical pressure, temperature, air-fuel ratio, type of fuel and rate of fuel flow etc. Rokke et al. [15] developed the NO_x estimation model based on parameters like cylindrical pressure, equivalence ratio and air-flow. Lefebvre et al. [16] developed the NO_x determination model based on the inlet cylindrical pressure, volume of the cylinder, adiabatic temperature, flow rate of air, maximum temperature. Odgers et al. [17] presented expression for determination of the NO_x by using parameters like inlet pressure, adiabatic temperature and combustion time. Bakken et al. [18] developed the NO_x relation for the gas turbine based on the inlet pressure, temperature and equivalence ratio. Kim et al. [19] have studied the response surface method for the $H_2/CO/CH_4$ gas turbine, and they have developed the formula of correlation coefficient of NO_x. The input parameters of equation are ratio of hydrogen, carbon-monoxide and methane respectively.

Most of the available NO_x prediction models are based on the combustion attributes as the input parameters. While, there is no prediction model of NO_x for HCNG engine which depends upon the operating conditions of the engine. The purpose of this study is to develop the NO_x emission model which can be used for the estimation of NO_x emission by substituting the operating condition such as the air-fuel ratio, manifold absolute pressure and hydrogen percentage. Hence, presented NO_x emission model can be used for the reduction of NO_x emission by varying the three main operating condition. Moreover, this NO_x estimation model is efficient in terms of cost and time.

Experiments have been performed on Dongfeng Engine under different air-fuel ratio, manifold absolute pressure and hydrogen percentage. The NO_x emission is curve fitted in sequence to the air-fuel ratio, manifold absolute pressure and hydrogen percentage at MBT spark timing and 1200 rpm. The validation results show that the z-confidence is about 95%.

2. METHODOLOGY

Experiments have been performed on turbo-charged, DongFung SI engine. The on-line mixing system of hydrogen and methane are same as used in previous researches [20]. The NO_x emission has been measured by the HORBIA-MEXA-7100 DEGR emission analyzer.

The NO_x prediction model has been developed using the MATLAB software with the help of tool curve fitting.

Table 1 - Specification of the Engine

Engine Manufacturer	Dongfeng Motor Co. Ltd., China

Specification	6-Cylinder, Turbocharged SI Engine
Bore (mm)	105
Displacement (mm)	120
Compression Ratio	10
Swept Volume (L)	6.234

3. NO$_X$ MODEL BY CURVE FITTING

The experiments have been performed at the MBT ignition timing and optimum speed. The air-fuel ratio, MAP and hydrogen fraction are input parameters of the program at engine speed of 1200 rpm and ST=30^o BTDC. Approximate 135 experimental data points have been used for the development of the program.

3.1. Air-fuel ratio & NO$_x$ emission

In the first step, the NO$_x$ emission has been curve fitted with respect to air-fuel ratio. The Gaussian function is suitable for curve fitting as shown in Eq (1) and Fig. (1).

$$NO_x = a \times [e^{-(\frac{b-AFR}{c})^2}] \quad (1)$$

The values of curve-fit coefficients a, b and c are tabulated in the Table 1

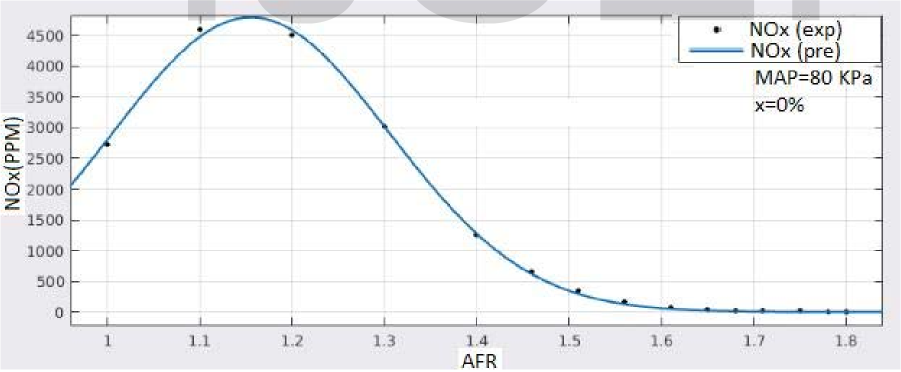


Fig. 1: NO$_x$ emission vs air-fuel ratio

Table 2: The Curve Fitted Coefficient at the different hydrogen percentage and MAP.

MAP (KPa)	H$_2$%(x)	a	b	c
50	0	1882	1.102	0.1567
	10	2773	1.037	0.2202
	30	8250	0.7979	0.3403
80	0	4947	1.156	0.2123
	10	5742	1.173	0.2326
	30	6234	1.21	0.247
105	0	6737	1.181	0.2342
	10	1.432×10^4	1.197	0.1299
	30	1.245×10^4	1.228	0.1869

3.2. Manifold absolute pressure & NO$_x$ emission

In the second step, the coefficients for x=0% have been curve fitted at different manifold absolute pressure.

$$NOx_{0HCNG} = a_1 \times [e^{-(\frac{b_1-AFR}{c_1})^2}]$$

(2)

$$a_1 = 88.58 \times MAP - 2567$$

$$b_1 = 0.001436 \times MAP + 1.03$$

$$c_1 = 0.001413 \times MAP + 0.08606$$

MAP is in kPa. The error has been found at x=0% & MAP=80 kPa as shown in figure 1. It is found that few errors have been seen in the NOx emission by Eq. (2). Therefore, after calculating the errors with respect to the experimental results, these errors is removed by curve fitting with air-fuel ratio as can be seen in the Eq 3.

$$NOx_{MAPerror} = a_2 \times [e^{-(\frac{b_2-AFR}{c_2})^2}]$$

(3)

Table 3: The curve fitted of a, b & c of different MAP with hydrogen percentage=0.

MAP (kPa) [0% H_2]	a_2	b_2	c_2
50	0	0	0
80	500.4	1.294	0.2188
105	0	0	0

The coefficients can be seen in Table 3 while the co-efficient in the table have been curve fitted with respect to MAP.

$$a_2 = -0.6672 \times MAP^2 + 103.4 \times MAP - 3503$$

$$b_2 = -0.001725 \times MAP^2 + 0.2674 \times MAP - 9.058$$

$$c_2 = -0.0002917 \times MAP^2 + 0.04522 \times MAP - 1.532$$

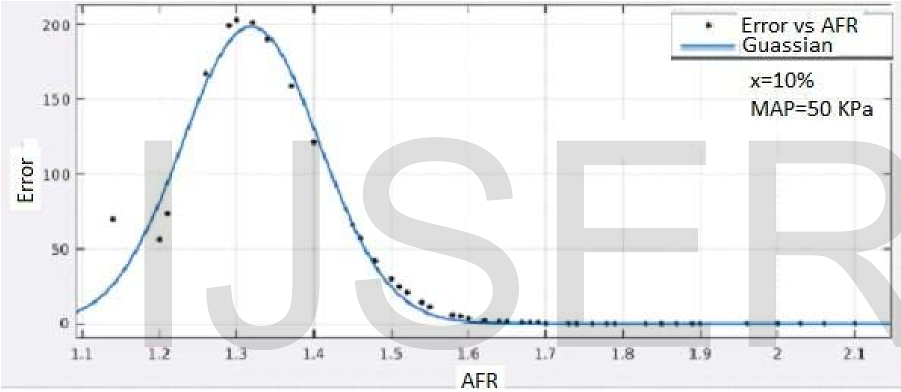


Fig. 2: The error of HCNG10 vs air-fuel ratio.

Fig. 3: The NO_x emission of hydrogen percentage=10 vs NO_x emission vs hydrogen percentage=0

$$NOx_{(HCNG0corrected)} = NOx_{(MAPerror)} + NOx_{(HCNG0)}$$

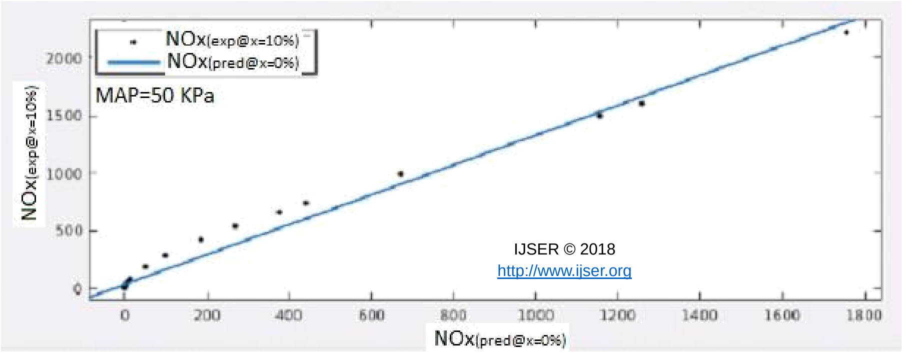
(4) The Eq. (4) is suitable in determination of NO_x emission for the compressed-natural gas at ignition timing= 30° BTDC and engine speed of 1200 rpm.

3.3. Hydrogen-percentage & NO_x emission

In the third step, the fraction of hydrogen has been introduced in the program. The equation for the NO_x emission of HCNG fuel is as follows:

$$NOx_{(H2percent)} = [1 + 2.3033 \times x] \times NOx_{(HCNG0corrected)} \quad (5)$$

The percentage error increases with the increase of input parameters. The error corrections have been done by



curve fitting by taking the error which were found previously as the basis with respect to the air-fuel ratio at MAP of 50 kPa as shown in the Eq. (6) as shown in figure 2.

$$NOx_{H2error} = a_3 \times [e^{-(\frac{b_3-AFR}{c_3})^2}]$$

(6)

The co-efficient at different hydrogen percentage at MAP of 50 kPa is shown in Table 4 and figure 3.

Table 4: The Curve Fitted Coefficient at different hydrogen percentage at MAP=50 kPa.

H_2%	a_3	b_3	c_3
0	0	Not zero	Not zero
10	198.9	1.319	0.1255
30	350.2	1.366	0.1169

The co-efficient in Table 4 have been curve fitted with respect to the hydrogen percentage

$$a_3 = -4108 \times x^2 + 2400 \times x + 4.84 \times 10^{-20}$$

$$b_3 = 0.235 \times x + 1.295$$

$$c_3 = -0.043 \times x + 0.1298$$

$$NOx_{(HCNGcorrected1)} = NOx_{(H2percent)} + NOx_{(MAPerror)} + NOx_{(H2error)}$$

(7)

Eq. (7) is good for the prediction of NO_x emission for x=0-0.3 at MAP of 50 kPa.

3.4 Error Correction

Error can be seen by applying Eq. (7) at different operating condition x=0-0.3 & MAP of 50-105 kPa. Combined error corrections have been made in order to improve the accuracy of the program.

3.4.1 Combined Error 1

The error corrections have been made with the predicted and experimental values by a line y=m×x. Then, the slope (i.e. m) have been curve fitted with respect to the hydrogen percentage. The general equation can be seen in the Eq. (8) while the individual can be seen in the Table 5.

$$NOx_{(combinederror1)} = a_0 \times x^2 + a_{10} \times x + 1$$

(8)

The equations in the Table 5 is curve fitted with respect to the manifold absolute pressure as shown in the following Eqs.

$$a_0 = 0.008976 \times MAP^2 - 1.435 \times MAP + 49.32$$

$$a_{10} = -0.001285 \times MAP^2 + 0.1672 \times MAP - 5.149$$

$$NOx_{(correctedcombined1)} = NOx_{(combinederror1)} + NOx_{(corrected1H2error)} \qquad (9)$$

f(x)	$NO_{x\{combinederror1\}}$	Formula
H_2=0%, MAP=50	1	$NOx_{combinederror1}=0\times x^2+0\times x+1$
H_2=10%, MAP=50	1	
H_2=30%, MAP=50	1	
H_2=0%, MAP=80	1	$NOx_{combinederror1}=-8.05\times x^2+0.005\times x+1$
H_2=10%, MAP=80	0.92	
H_2=30%, MAP=80	0.77	
H_2=0%, MAP=105	1	$NOx_{combinederror1}=-2.47\times x^2-1.758\times x+1$
H_2=10%,	0.8	

MAP=105		
H_2=30%, MAP=105	0.255	

Table 5: Combined Error 1.

3.4.2 Combined Error 2

The predicted results of Eq. (9) still have error. Thus, this error is then curve fitted with respect to the air-fuel ratio as can be shown in Eq. (10)

$$NOx_{combinederror2} = a_4 \times [e^{-(\frac{b_4 - AFR}{c_4})^2}] \tag{10}$$

The coefficients can be shown in Table 6. These co-efficient have been curve fitted with respect to the hydrogen percentage. The co-efficient of these new equations have been curve fitted with respect to the manifold absolute pressure as shown in the following equations.

Table 6: Combined Error 2.

MAP (KPa)	**H_2%**	a_4	b_4	c_4
50	0	0	Not zero	Not zero
	10	0	Not zero	Not zero
	30	0	Not zero	Not zero
80	0	0	Not zero (1.4325)	Not zero (0.09085)
	10	235.9	1.432	0.1152
	30	1310	1.431	0.1639
		$1.004\times10^4\times x^2+1335\times x+1.271\times10^{-21}$	$0.005\times x+1.4325$	$0.2435\times x+0.09085$
105	0	0	Not zero (1.467)	Not zero (-0.1446)
	10	9267	1.194	0.06836
	30	4.914×10^4	0.6479	0.4942
		$3.557\times10^5\times x^2+5.71\times10^4\times x-3.81\times10^{-20}$	$-2.731\times x+1.467$	$2.129\times x-0.1446$

$$a_4 = [0.128 \times e^{0.1413\times MAP}] \times x^2 + [0.008041 \times e^{0.1502} \times MAP] \times x + [-1.576 \times 10^{-21} \times MAP + 1.273 \times 10^{19}]$$

$$b_4 = [-0.109 \times MAP + 8.718] \times x + [0.0014 \times MAP + 1.32]$$

$$c_4 = [0.07542 \times MAP - 5.79] \times x + [-0.009418 \times MAP + 0.8443]$$

$$NOx_{[HCNG]} = NOx_{[combinederror1]} + NOx_{[combinederror2]} \tag{11}$$

Thus, Eq. (11) is suitable equation for the prediction of NO_x emission of HCNG engines. mixture.

3.5. Validation

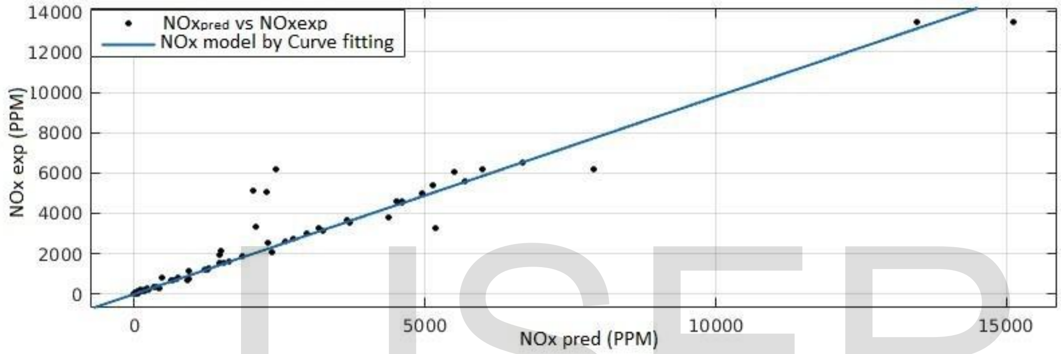
For the validation purpose MATLAB program has been coded. The estimated results and experimental results have been curve fitted by a simple slope equation (y=m×x) whereas the *m*=0.9775 and the limit is [0.9399,1.015] which can be seen in Fig. (4). The statistical results are as follows: the z-confidence bound interval is 95%, R-square=0.9386, RMSE=574.2 and SSE=4.386×10^7. In simple words, R-square=0.9386, means that the fitted regression line is 93.86% close to the actual data. While, z=95%, means that confidence of program is about 95%.

The program accuracy is found to be maximum within the range of air-fuel ratio= 1 to 1.5 whereas the average error is 7.55%. At the same time some of the operating conditions at x=30% have the error of near about 50%. Thus, the error and hydrogen-fraction has the direct relation. While, average error of compressed natural gas is about +2%.

4. CONCLUSION

The statistical approach has been applied to evaluate the NOx emission of HCNG engines. The presented NOx model has three input parameters i.e. air-fuel ratio, MAP, and hydrogen-percentage. Therefore, once this model has been developed then it is quite easy to estimate the NOx emission with less time. Experiments have been performed on HCNG engine by varying the air-fuel ratio, manifold absolute pressure and hydrogen percentage at MBT ignition timing and optimum speed. The experimental results of NO_x emission have been curve fitted by using MATLAB. The salient feature of conclusions is as follows:

1. The Gaussian function is most suitable equation for the prediction of NO_x emission.



2. The confidence of program is about 95% and fitted regression line is about 93.86% close to the actual data. Both the values are pretty good.
3. The program is more accurate for the air-fuel ratio 1 to 1.5 where the average error is found to be only 7.55% (less than 10%).
4. The average error of compressed natural gas is about +2%.
5. The error is about 50% at some operating conditions of 30% hydrogen percentage.

NOMENCLATURE

ANN: artificial neural network
BSFC : brake specific fuel consumption
BTDC: before top dead center
CA: crank angle
HCNG: hydrogen enriched compressed natural gas
MBT: maximum brake torques
MAP: manifold absolute pressure
NG: natural gas
PPM:part per million
RPM: revolution per minute
RMSE:root mean square error
SSE:sum of square error
SVM:support vector machine
x=hydrogen fraction

SUBSCRIPT

a, b, c: co-efficient of gaussian function

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