PREDICTION OF PERFORMANCE AND EMISSION OF COMPRESSED NATURAL GAS (CNG) IN A SUPERCHARGED DIRECT INJECTION SPARK IGNITION ENGINE USING ARTIFICIAL NEURAL NETWORK

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ABSTRACT

Emissions of greenhouse gases such as carbon dioxide, nitrogen oxide and some hydrocarbons have been the main causes of global warming and have posed severe impacts on climate changes. Consequently, the focus on sustainable developments has swiftly grown in recent years. The utilisation of Compressed Natural Gas (CNG) in the spark ignition (SI) engine or using as dual fuel in compression ignition (CI) engine is getting remarkable attention nowadays. In this paper, performance and emission of CNG in supercharged direct injection spark ignition engine were predicted via Artificial Neural Network (ANN). The Levenberg Marquardt training algorithm was used due to its fast response, easy operation and high accuracy. The models' results are compared with experimental results available from a previous study by the author. It was observed that R^2 values for both performance and emission of CNG were higher than 98%, indicating good prediction. Following the training, high accuracy with value higher than 95% was observed for both analyses. Hence, it can be concluded that ANN is a promising technique for the prediction of performance and emission of CNG in direct injection spark ignition engine that consists of numerous inputs and output conditions.

Keywords: *Natural gas, CNG, supercharging, artificial neural network*

INTRODUCTION

The consumption of fossil fuel has grown by 36% over the last 15 years due to the steady growth of world population and advancement in life quality [1]. This has led to climate changes in the same years [2]-[4]. Transportation sector has also taken significant share in the global warming due to a dramatic increase in number emanating 23% carbon dioxide emissions [5]. Consequently, the road transport sector requires more secure and sustainable fuel sources in the future. To reduce the dependence on fossil fuels in the transportation sector, alternative ways include modern SI engines with three-way catalysts that emit low amounts of toxic emissions, hybrid systems and high-pressure direct fuel injection systems. Improving fuel economy such as operating SI engine and HCCI with diluted mixture or EGR could also result in low combustion temperature, low heat and pumping losses using fuel with higher hydrogen to carbon ratio that reduces emissions [6],[7]. Natural gas is one of the most established alternative fuels that consist of various gas types with methane constituting more than 90% [8]. When comparing to stoichiometric condition, in ultra-lean condition, the wider flammability limit, higher compression ratio due to high octane number and lower peak temperature forms higher knock resistance in natural gas [9]. CNG could also improve the cold and hot startability in the engine as it prevents wall wetting effects in the cylinder and this helps save fuel consumptions [10],[11].

There are mainly two options to convert the conventional SI engine to natural gas engine: bi-fuelled engine and dedicated CNG engine. For bi-fuelled spark ignition petrol engines, some modification must be carried out including installing of gas carburettor, regulator, shut-off valve, control system and fuel storage tanks for normal operation of natural gas fuel [12]. When it comes to diesel CI engines, they consist of dual-fuelled engines and dedicated natural gas engines. As natural gas engine has a lower compression ratio compared to a diesel engine, it has low efficiency and higher heat loss, and friction could be observed during openings of exhaust valves [13]. As natural gas has low cetane number, the diesel would act as pilot fuel for normal ignition to occur and overcome problems of auto-ignition of natural gas [14]. However, this dual fuel mode would have lower efficiency and power output compared to conventional diesel engines. By using high pressure direct injection, natural gas can gain 9% in peak torque [15],[16]. It was also reported that the mixing quality could be improved by passing the air-fuel mixture through the turbocharger and rotary compressor wheel [17],[18]. In addition, a long inlet pipe between the mixer and cylinder can give longer time for air and gas mixing and forms better mixture [19].

In recent years, there is also a development of a new direct injection system called ducted fuel injection (DFI). By using DFI, there are several benefits obtained, such as increasing the turbulence effect due to increased velocity gradient, preventing the soot formation at richer air-fuel ratio, reducing the auto-ignition zone, enriching lean air-fuel mixture and hence enhancing combustion efficiency and reducing hydrocarbon and carbon monoxide emissions [20]. There is an increasing interest to study the effects of supercharging on the performances and emissions of the CNG in direct injection engines due to its benefits as vehicular fuel and advancement of the current technology in minimizing the performance gap of alternative fuels. However, due to many inputs in the engine tests, Artificial Neural Network having faster response and high accuracy was reported to be a valuable tool to predict engine operating parameters.

Artificial Neural Network (ANN) has become a commonly used tool in various fields due to its capability to solve non-linear complex problems, detect high fault tolerance, adapt for exact solution, define the relations between input and output parameters, and have local memories to store the available information [21]. Several studies on engine performance were carried out using ANN. Since it is very costly and time-consuming to test the nano-particles of the fuel, ANN can be used for prediction and it also reduces the hefty tests [22]. The mean value modelling is mostly used in the engine study by breaking down the interface into subsystems, which can be described by different equations. For example, research on air flow rate for variable valve timing engines was carried out by Wu et al. [23] and the result showed high accuracy within the error range of 10%. Besides, studies on meta-modelling by Papadimitriou et al. using the neural network reported qualitative and quantitative engine performance with only 0.54% error in average fuel consumption model. From Yusuf et al. work, the research by Narendra and Parthasarathy also determined the usage of the neural network in approximation of output torque of engine [24]. The work of predicting volumetric efficiency of a downsized turbocharged spark ignition engine using Artificial Neural Network also showed satisfactory results.

Yusuf et al. [25] tested the reliability of the Artificial Neural Network model to predict the exhaust temperature, engine power and specific fuel consumption with inputs parameters of engine speed, injection timing and mean effective pressure in gasoline engines. In their study, 3 to 15 neurones were created to determine optimum number of hidden layer neurones. It was found that there was only a relative error of 2.43% in specific fuel consumption, 1.18% in the prediction of exhaust temperature and 2.67% for engine power prediction when compared to the real model. Besides, a Matlab neural network model was created by Liu et al. [26] to predict the misfire detection of turbocharged diesel engines. Three back propagation model with inputs of engine speed, boost pressure, intake temperature, exhaust temperature, water temperature and fuel consumption were selected. The prediction was successful as the mean square error was only 0.001. Though ANN has high accuracy of prediction in wide applicability, there have been limited studies performed to predict performance and emission parameters of CNG in supercharged direction injection spark ignition engines. The objective of this study was, therefore, to predict the performance and emission of CNG in a supercharged DI SI engine via ANN.

METHODOLOGY

Artificial Neural Network was used to predict performance and emission of compressed natural in supercharged DI SI engine. Data used and trained in ANN in this study were found from previous study by the author. The engine used for the experiments was a 4-stroke direct injection spark ignition with a compression ratio of 14. The experiments were conducted at different boost pressures for stoichiometric air-fuel ratio for two types of injection timings. In regard to Artificial Neural Network (ANN), there are several classifications in which feed forward network is the most used due to its capability to detect fake and missing data during processing. Feed forward network consists of single layer, multiple layer and radial basis function [21]. Single layer perceptron operates in unidirectional between input and output with the equation, $a = f(w_1 p_1 + w_2 p_2 + w_3 p_3 + \ldots + w_R p_R + b)$; where a = output, w_i = weight, b = bias term and p_1 = input.

Multiple Layer Perceptron (MLP) is one of the common forms of the ANN that has an input layer, some hidden layer and output layer [27]. Besides, the utilisation of the Back-Propagation learning for the complex real world situation is powerful but limited with the slow learning speed [28]. MLP is able to model broad spectrum, useful for application before discovering the analytic method and captures non-linear dependencies between input and output compared to the single layer. The general equation for MLP is $a^3 = y = f^3\,(LW^{3,2} f^2\,(LW^{2,1} f^1\,(IW^{1,1} p + b^1) + b^2) + b^3)$.

In this paper, feed forward back propagation was used to solve simple problems in a single layer with less computational time and solve complex problems in multilayer, but with long training time. Engine speed was considered as an input whereas other features such as torque, Brake Specific Fuel Consumption (BSFC), Brake Mean Effective Pressure (BMEP) and power are considered as target values in performance predictions. In predicting the emission of CNG, the input considered was engine speed whereas hydrocarbon, carbon monoxide and nitric oxide as target values. In the model, one input was connected to 10 hidden layers for interpretation before sending to one output layer, from which the output based on the target value was found. Figure 1 shows process flow of ANN.

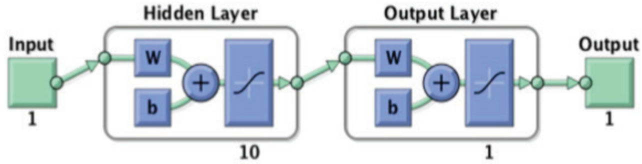


Figure 1 Process flow of ANN [29]

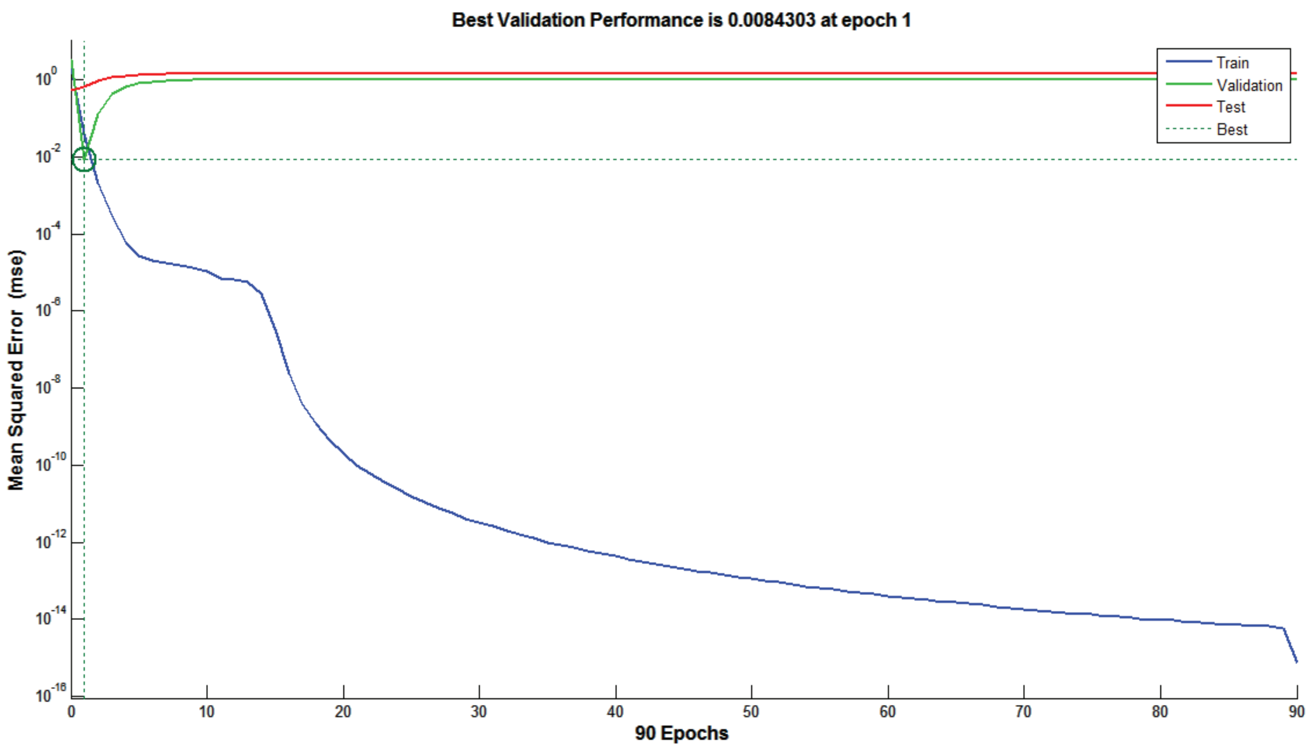
In addition, the data were trained in the Levenberg-Marquardt methods as it is the fastest back propagation algorithm in the toolbox of Matlab. The maximum epochs of 1000 were set to get accurate results. Moreover, the performance of the simulation was tested using the mean square error. The performance graphs were plotted based on the iteration to show relationship between training, validation and test data to prevent overfitting of the graph and ensure that the test and validation curves are similar. In this study, the R value is ensured to be more than 0.99 so that the accuracy would be enhanced as the value is more than 90%.

RESULTS AND DISCUSSION

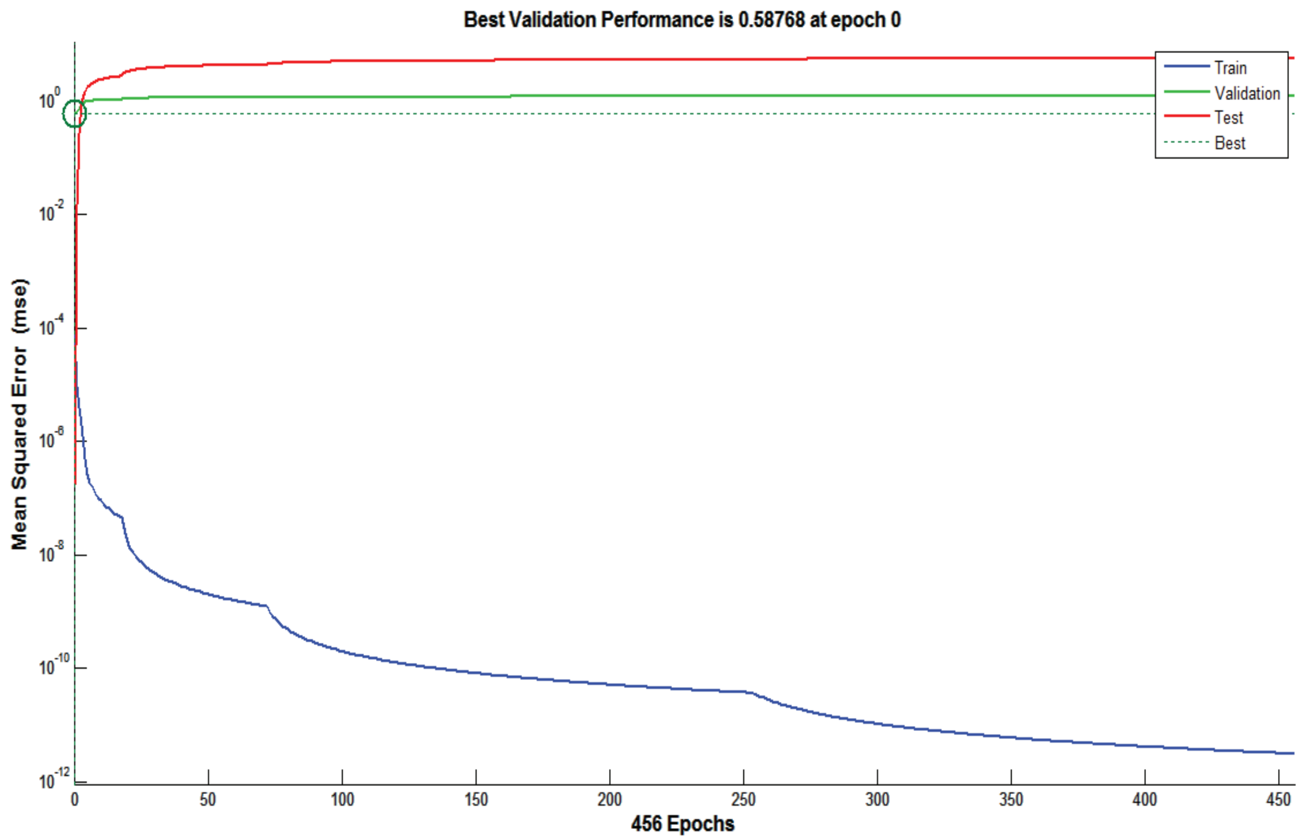
Performance of CNG in Direct Injection Supercharged SI Engine

The regression and performance based on the mean square error was tested using ANN comparing the results between the simulated and experiments. The regression formula between the target value (value from real experiment) and the output value (value from simulation) can be found from the regression plot. The performance plots show the gap between the training and validation data fitted each other by showing the mean square error for each of the simulation.

The performance graph based on the mean square error between output value and target value is shown in Figure 2. Training state plot is also depicted in Figure 3. The best validation performance is at epoch value of 1 at which train and validation results are almost similar with the performance of 0.0084303 at that state. The regression plot, depicted in Figure 4, shows that the regression value displaying empirical relation between inputs and outputs in naturally aspirated value is 0.99732 and regression formula can be given as Output=1*Target+–0.028. From the

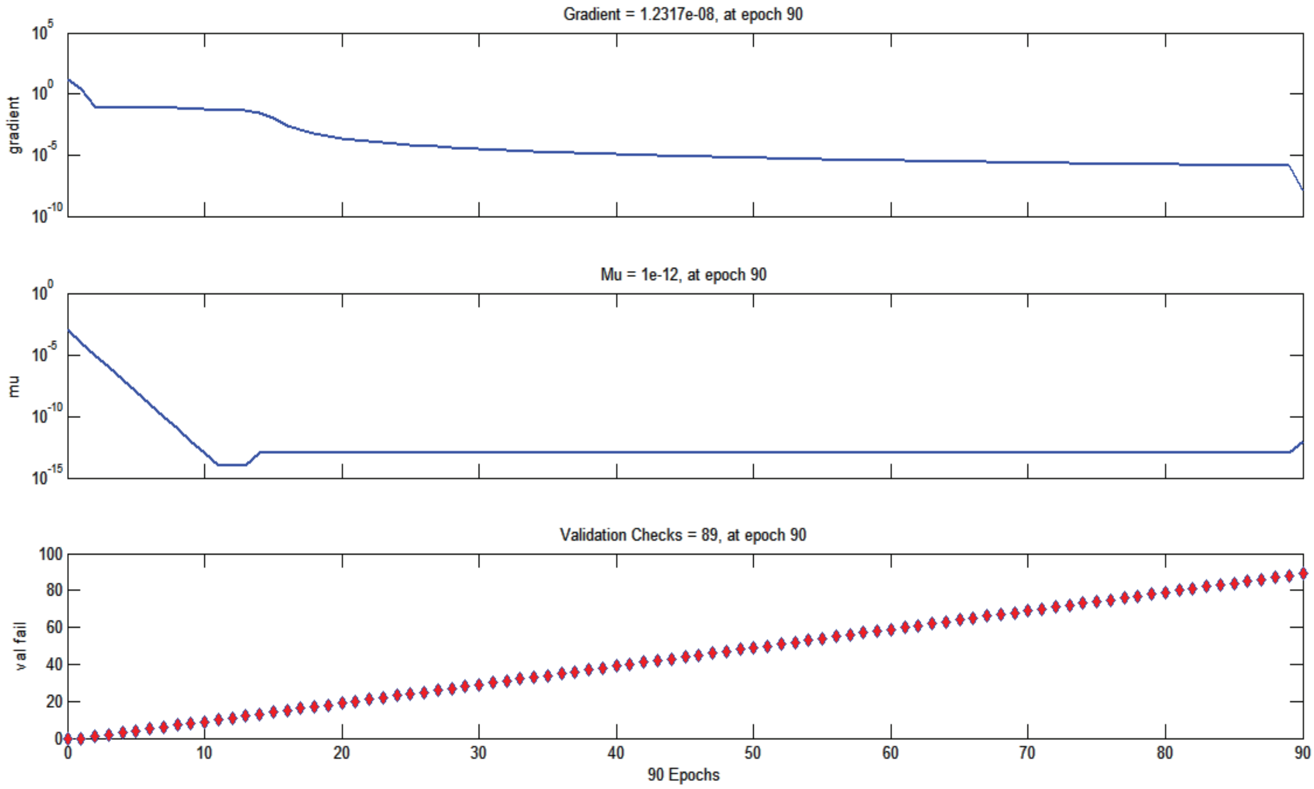


(a)



(b)

Figure 2 Performance plot a) 180°BTDC b) 300°BTDC



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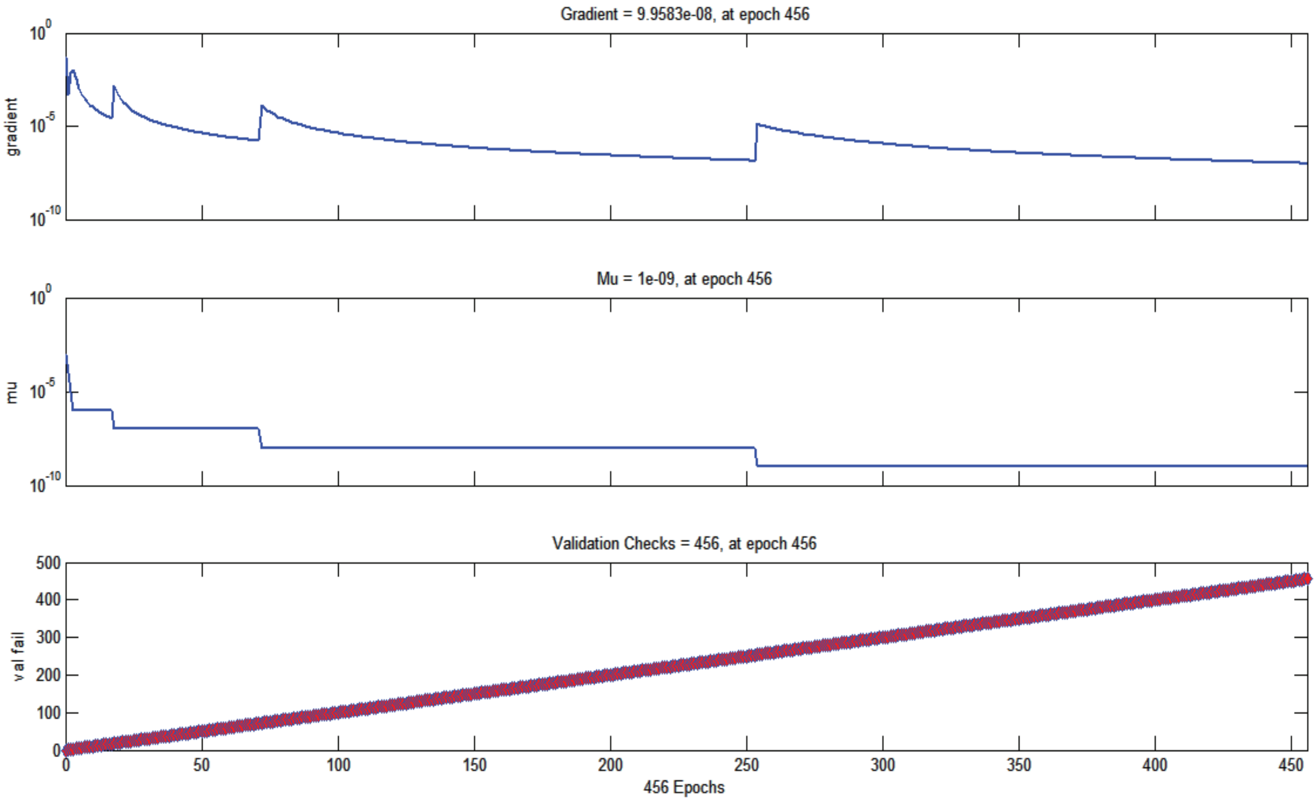

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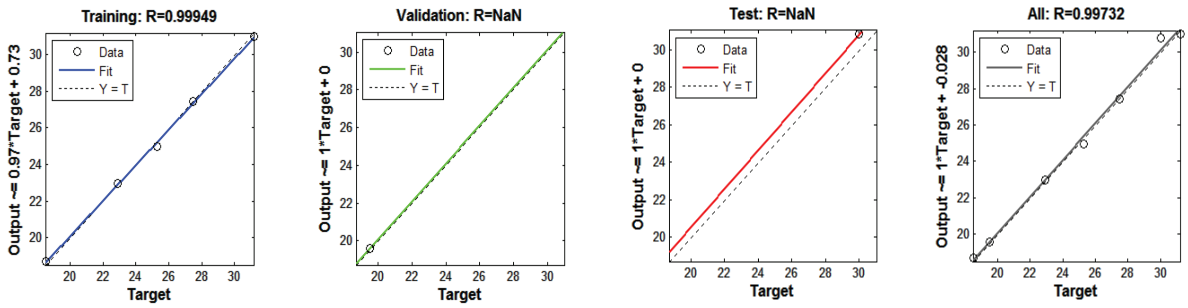
Figure 3 Training state plot a) 180°BTDC b) 300°BTDC



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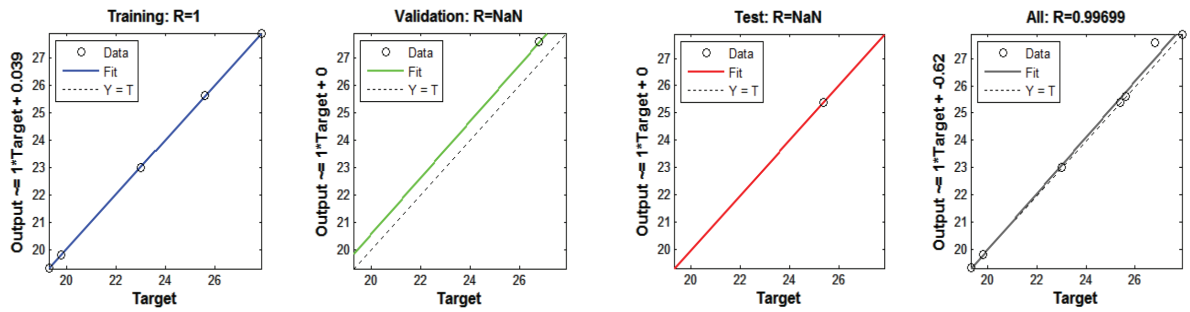
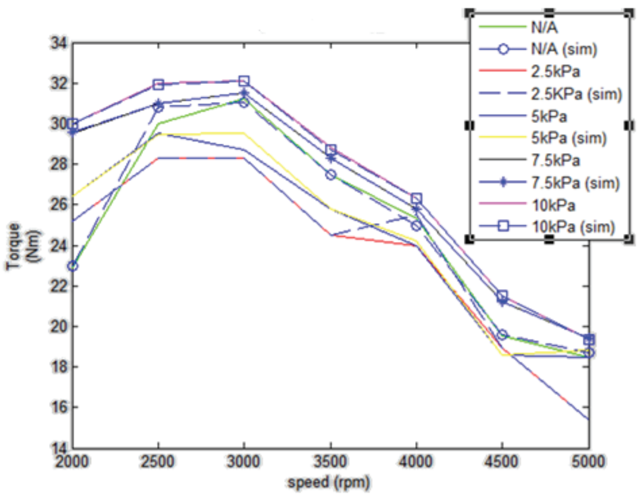


(b)

Figure 4 Regression plot a) 180°BTDC b) 300°BTDC

performance plot of 300°BTDC, it can be observed that best performance is valid at epoch value of 0 with the mean square error of 0.58768. The regression plot shows the R value of 0.99699 and with equation given as Output=1* Target+–0.62.

Figure 4 shows regression plots for both partial and port injection timings. It was be found that the R value is more than 0.99 and hence higher accuracy can be achieved with the value more than 98%. Besides, the regression formula shows that the output value (simulation result) does not deviate significantly from the target value (experimental result). It is obvious that the simulation graph pattern is almost similar with the real experiment patterns for different boost pressures at different speeds, as can be observed in Figure 5.



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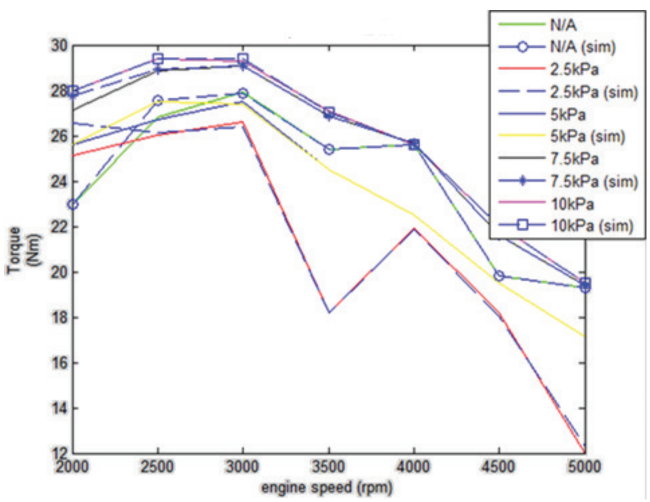


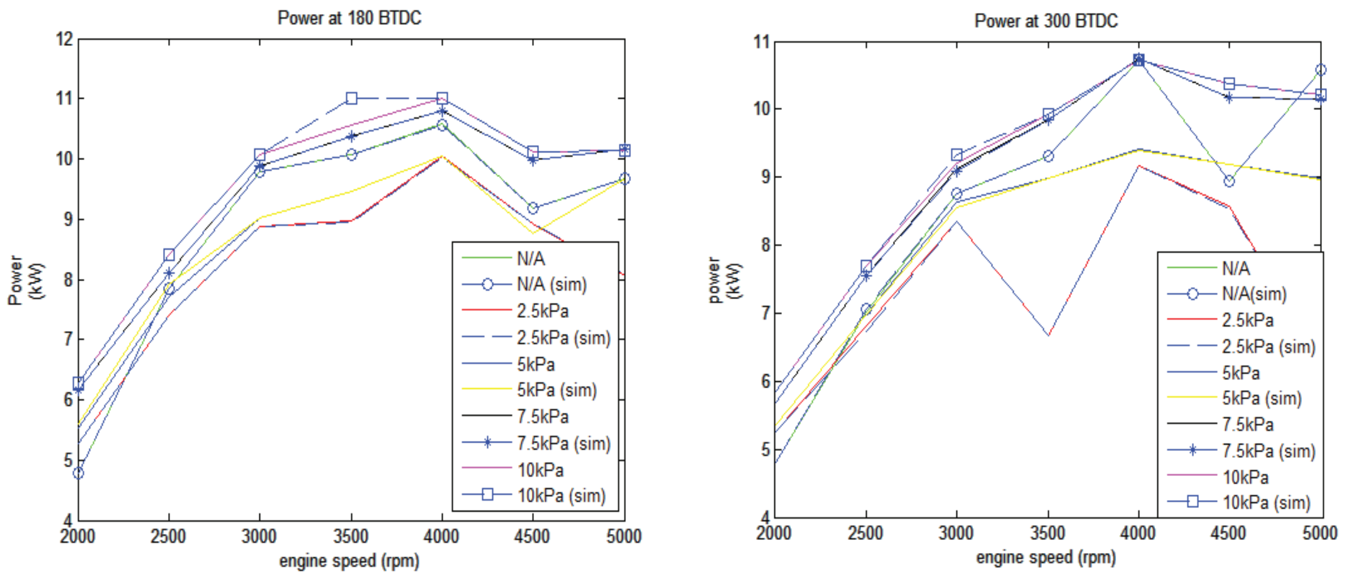
(b)

Figure 5 Engine Torque for different boost pressures at a) 180°BTDC b) 300°BTDC

The trends of torque values for both injection timing were also similar.

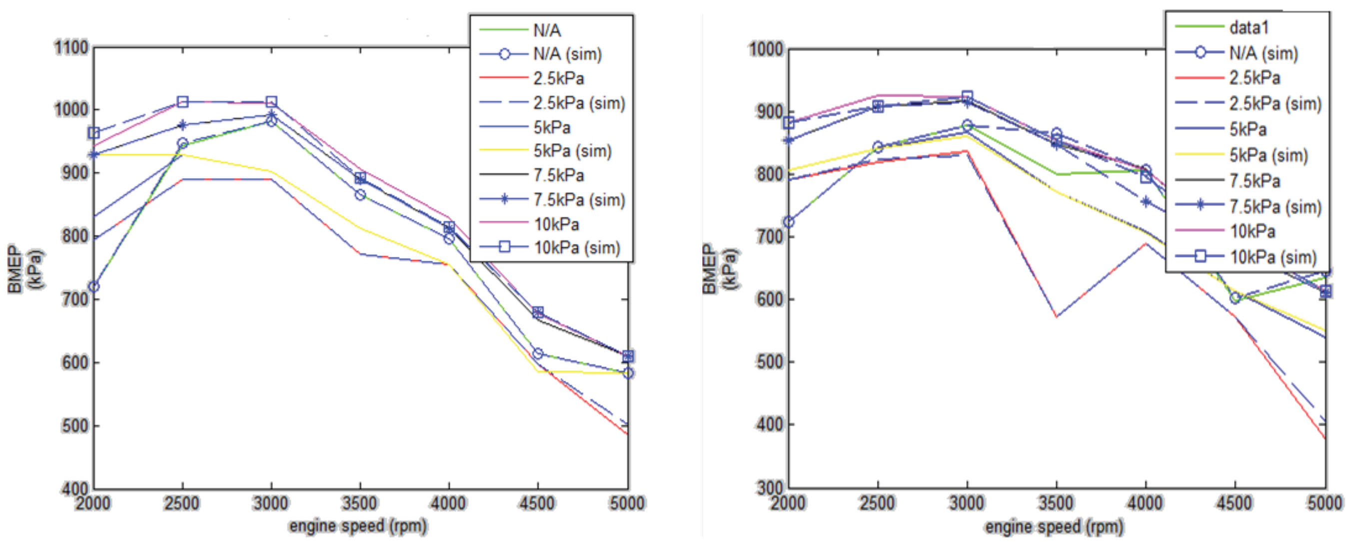
Figure 6 shows the power output for 180° and 300° BTDC injection timings at different engine speeds. The regression plot of power simulation provided R value of more than 0.99 and value more than 0.98 or 98%, showing higher accuracy and preventing far deviation of the simulation result (output) from experimental result (target). The engine power reached peak value at about 3500 rpm for both experimental and modelling analysis, with similar trends at both injection timings.

Figure 7 shows BMEP for 180° and 300° BTDC injection timings. In the simulation of BMEP of engine at 180° BTDC, the R values for the regression plots are more than 0.97 with the value more than 94%. The maximum BMEP value of more than 1000 kPa for boost pressure of 10 kPa is found at engine speed of 3000 rpm.



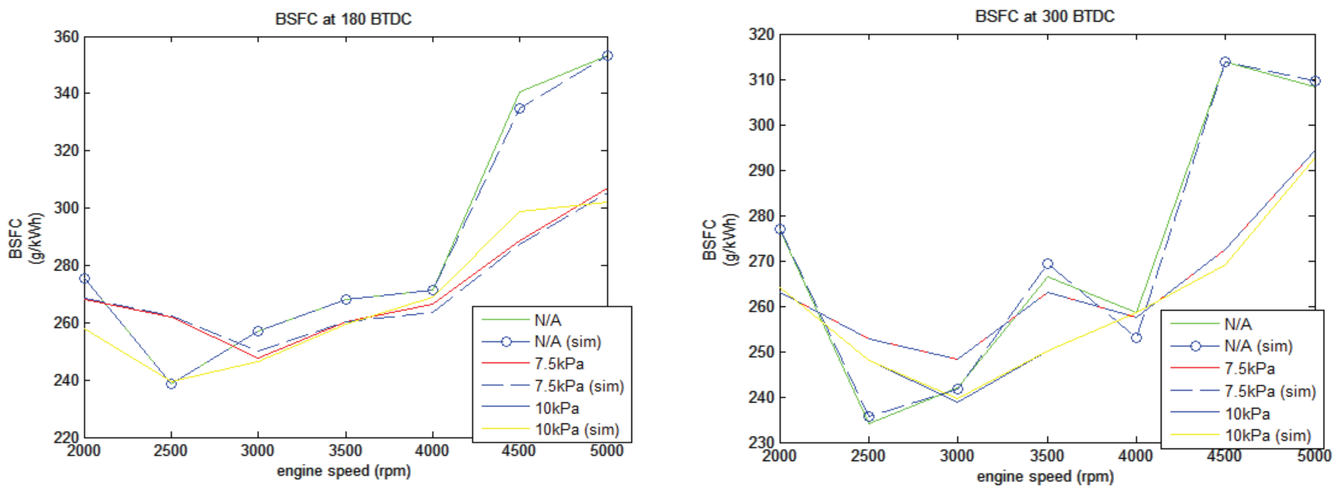
(a) (b)

Figure 6 Power output at (a) 180°BTDC b) 300°BTDC injection timing



(a) (b)

Figure 7 BMEP versus engine speed at a) 180°BTDC b) 300°BTDC injection timing



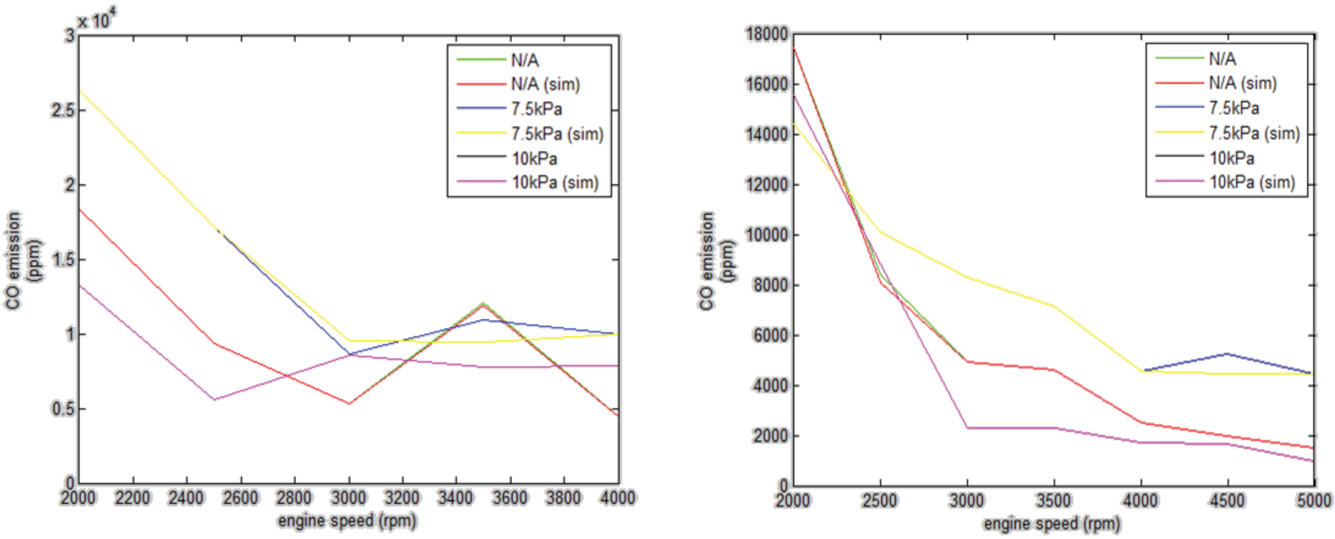
(a) (b)

Figure 8 BSFC versus engine speed at a) 180°BTDC b) 300°BTDC

From the regression plots, shown in Figure 8, it was found that the R value is more than 0.99 and hence value is higher than 98%, ensuring higher accuracy to reduce the deviation from real experimental results due to error. In high load, richer air-fuel mixture is required to prevent knock in supercharged engine. The richer air-fuel mixture can be generated by using the direct injection as it reduces the amount of fuel escaped from combustion chamber [30].

Emission of CNG in DI SI Engine

Figure 9 shows CO emissions for partial and port injection timings at different boost pressures. The R value for this simulation is higher than 0.99 with value of more than 98% revealing higher accuracy of the model. The CO emission was minimal at low engine speeds of lower than 3000 rpm. The lean condition caused by supercharging in the engine provides low CO emission as oxygen content is higher [31].



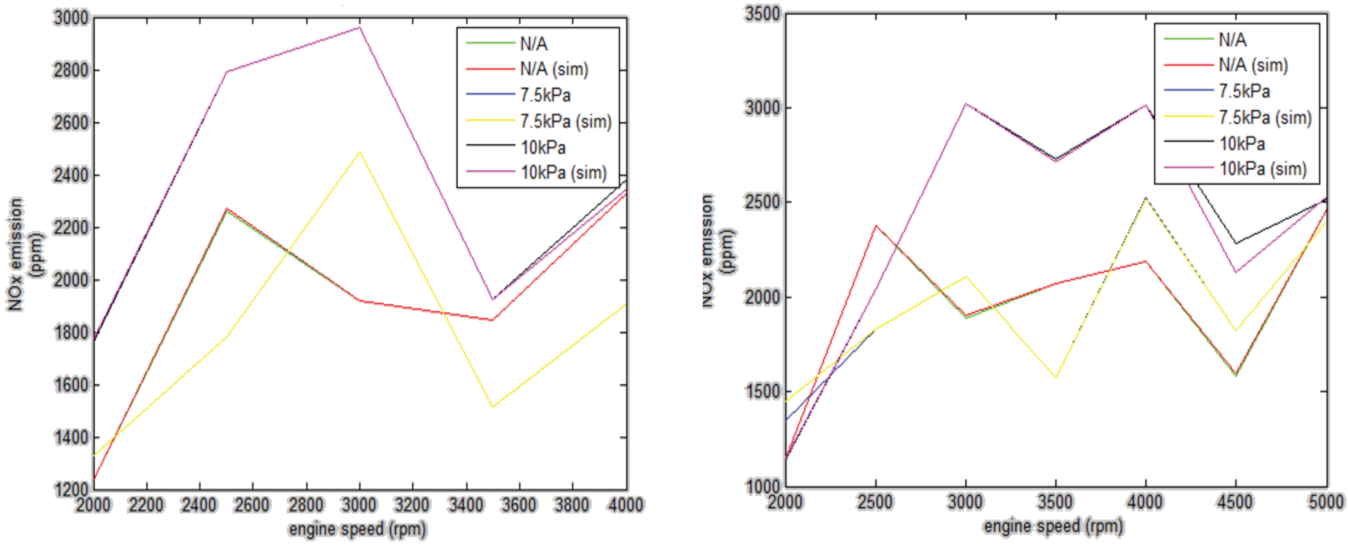
(a) (b)

Figure 9 CO emission over engine speed at different boost pressure a) for partial injection timings b) port injection timings

In addition, by supercharging, the formation of carbon monoxide is inhibited due to sufficient amount of oxygen in the combustion chamber [32],[33]. The air fuel mixture would become rich for naturally aspirated condition at high speed. The tendency to knocking and high emission of carbon monoxide and unburned hydrocarbons in rich condition makes it undesirable with lower thermal efficiency [5]. This condition can be minimized by increasing boost pressure that helps provide lean condition at high speeds.

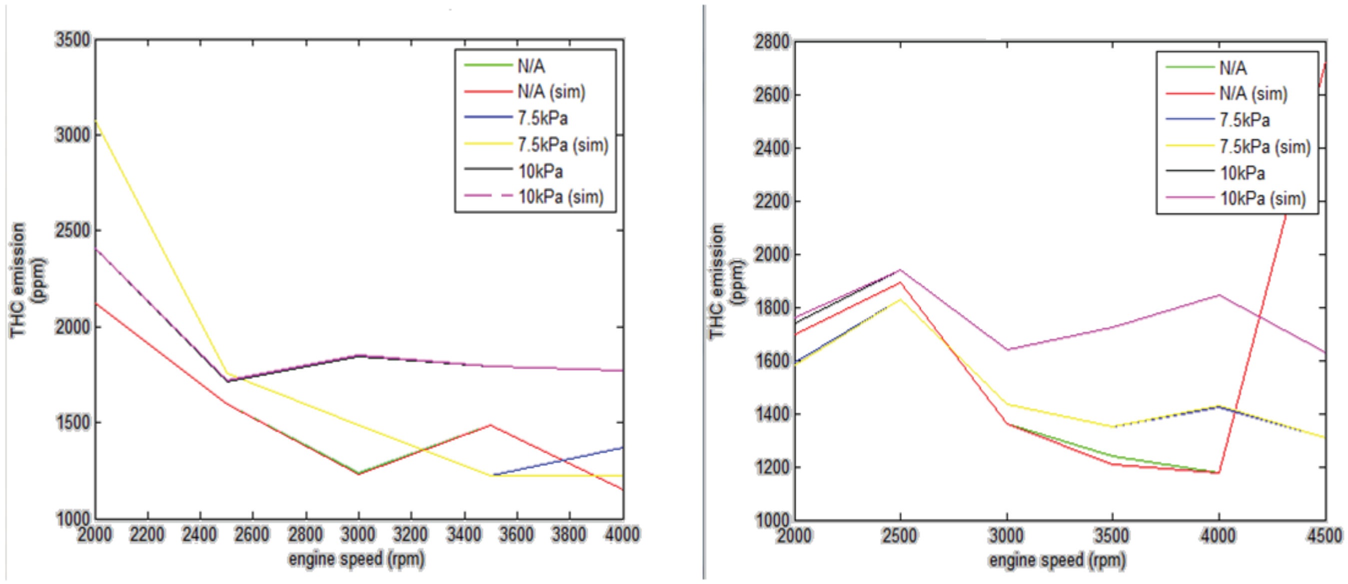
Figure 10 depicts NOx emission for both injection timings: partial and port. It can be seen that R value is more than 0.99 with value of higher than 98% indicating high accuracy. The use of an increased boost pressure was reported to increase NOx emission at higher engine speed, with a significant amount observed at engine speed of 3000 rpm. The trends almost appear the same for both injection timings.

The Total Hydro Carbon (THC) emission versus engine speed is shown in Figure 11. In this case, the R value is



(a) (b)

Figure 10 NOx emission versus engine speed at different boost pressure a) for partial injection timing b) port injection timing



(a) (b)

Figure 11 THC emissions a) at partial injection timing b) port injection timing trained to be higher than 0.99 to get value of more than 0.98 or 98% to ensure high accuracy. A closer prediction between the model and experimental results was also observed.

CONCLUSION

This paper investigates the reliability of ANN algorithm in the field of performance and emission of supercharged direct injection spark ignition engine running on compressed natural gas. The Levenberg Marquardt training algorithm was used due to its fast response, easy operation and high accuracy. The input was connected to one hidden layer with 10 hidden neurones and the output was simulated based on the training activities in the hidden layer. Comparisons between the models and experimental results are made to observe the accuracy of the models. After training, high accuracy with more than of 95% was observed in the performance and emissions of the CNG in supercharged direct injection spark ignition engine. Hence, it can be concluded that ANN is a promising technique for the prediction of performance and emission of CNG in supercharged DI SI engine consisting of many inputs and conditions.

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