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Application of Artificial Intelligence to Predict the Performance and Exhaust Emissions of Diesel Engine Using Rapeseed Oil Methyl Ester

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Abstract

Artificial neural network (ANN) in artificial intelligence is an implementation of an algorithm inspired by research into the brain. This paper deals with artificial neural network modeling of a diesel engine to predict the engine performance and exhaust emission characteristics. Experiments were conducted on a single cylinder four stroke diesel engine fuelled with diesel as well as various percentages of blends of rapeseed oil methyl ester with diesel at different loads to acquire data for training and testing the proposed ANN. To train the network, biodiesel blend percentage, engine load, specific fuel consumption and exhaust gas temperature were used as the input variables where as the engine performance together with engine exhaust emissions were used as the output variables. Online back-propagation algorithm was used to train the network. ANN model can predict the engine performance and exhaust emissions quite well with correlation coefficients with very low root mean square errors.

Keywords: Artificial Neural Network; Back propagation algorithm; Compression ignition engine; Rapeseed oil methyl ester.

1. Introduction

Diesel engines are efficient power machinery for automotive applications due to their better fuel economy compared to gasoline engines. However, stringent emission regulations and future depletion of petroleum reserves force us to explore new technologies to develop an alternative fuel as well as to reduce

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pollutant emissions. Biodiesel is an alternative, renewable, clean diesel fuel made by conversion of the triglyceride fats to esters via transesterification with methanol or ethanol. The triglyceride fats used for making biodiesel can be any kind of vegetable oil, waste oil from cooking or industry and animal fats [1-5]. Biodiesel could be used directly in diesel engine in blends or in neat form [6-7]. Many research projects have been conducted to examine emissions from biodiesel. Most of these studies showed that biodiesel could effectively reduce particulate matter, dry soot, carbon monoxide and unburnt hydrocarbon but with a slight increase in nitrogen oxide emissions relative to diesel fuel [8-10]. Manufacturers and the researchers are interested in knowing the performance of diesel engine for various proportions of biodiesel blends. This requirement can meet either by conducting comprehensive testing or by modelling the engine operation. Testing the engine under all possible operating conditions and fuels are both time consuming and expensive, on the other hand developing an accurate model for operation of diesel engine fuelled with blends of biodiesel is too difficult due to the complex processes involved. As an alternative, the performance and exhaust emissions of engine can be modelled using ANNs. This new modelling technique can be applied to estimate the desired output parameters when enough experimental data is provided.

The digital computer provided a rapid means of performing many calculations involving ANN methods. Along with the development of high speed digital computers, the application of ANN approach could be progress a very impressive rate. In recent years, this method has been applied various disciplines including automotive engineering, in forecasting of engine thermal characteristics under different working conditions. The prediction by a well trained ANN is much faster than the conventional simulation programs or mathematical model as no lengthy iterative calculations are needed to solve differential equations using numerical methods. They have been in diverse applications in control systems, robotics, pattern recognition, forecasting, medicine, power system, manufacturing, optimization and signal processing [11]. Neural networks were used for studying the effect of cetane number on the diesel engine exhaust emissions [12]. The use of ANN for modelling the operation of internal combustion engine is a more recent progress. This has been used for the prediction of emissions from a diesel engine and gasoline engine [13-19]. They have been used for the prediction of diesel emissions using in cylinder combustion pressure [20]. This technology was also used for the modelling of valve timing in s S.I. Engine [21]. Some researchers studied this method to predict internal combustion engine characteristics. Artificial neural network approach has been used in forecasting engine systems reliability [22], to predict diesel lubricity [23], for diesel engine control design [24], in automotive engine management systems [25], and to model the intake manifold and throttle body processes in an automotive engine [26]. In the existing literatures, it was shown that the use of ANN is a powerful modelling tool that has the ability to identify complex relationships from input-output data. In this study, the applicability of an artificial intelligence i.e., use of ANN with online back propagation algorithm for determining the performance and exhaust emissions of a diesel engine fuelled with biodiesel blends viz., 10%, 20%, 30% & 40% by volume was investigated. Because online back propagation algorithm with gradient descent and gradient descent with momentum are very slow for practical problems since they require a slow learning rate for stable learning.

2. Materials and Methods

Crude rapeseed oil; methanol; sodium hydroxide as catalyst, which are required for transesterification process; anhydrous sodium sulphate; and concentrated hydrochloric acid which was used in bubble washing process, were procured from M/S Ganapathy trading company, Chennai. Transesterification process was carried out for the preparation of rapeseed oil methyl ester as per the procedure mentioned in Deepak Agarwal et.al [7]. The bubble wash was taken by mixing methyl ester with distilled water to remove excess of alcohol, catalyst and glycerol. Then to remove the moisture content in the methyl ester, it was treated with anhydrous sodium sulphate, which is commonly used as moisture absorbing agent. Table 1 indicates the properties of bio-diesel and commercial diesel fuel. Figure 1(a) shows the transesterification setup and Figure 1(b) shows the separation process of glycerol from rapeseed oil methyl ester using separating funnel. Characterization of diesel and bio-diesel are as per ASTM standards.

A stationary single cylinder, water cooled, four stroke, direct injection diesel engine is used for the present study. The load on the engine is varied with the help of the controller provided with electrical dynamometer. Technical details of the engine are given in Table 2. A data acquisition system is used to capture and record the engine parameters. Fuel flow rates are measured using an electronic weighing scale. Exhaust gas temperature is measured using the thermocouples. AVL-5 gas analyzer is used for the measurement of exhaust emissions. Short term performance tests were carried out on the engine with diesel to generate the base line data; subsequently B10R (10% rapeseed oil methyl ester + 90% diesel by volume), B20R (20% rapeseed oil methyl ester + 80% diesel by volume), B30R (30% rapeseed oil methyl ester + 70% diesel by volume) and B40R (40% rapeseed oil methyl ester + 60% diesel by volume) was used to evaluate its potential suitability as fuel. The properties of all the fuels were determined as per the ASTM standard and presented in Table 2. The percentage of blend and load were varied and engine performance measurements such as brake specific fuel consumption, exhaust gas temperature and emissions such as CO_2, NO_x were measured to evaluate the behaviour of the diesel engine. The engine was run at the rated speed of 1500 rpm for few minutes to attain steady state before the measurements were taken. The experiments were repeated and the average values were taken for performance and emission measurements.

Fig. 1(a) Transesterification setup; (b) Separation process

Table 1. Properties of diesel and rapeseed oil biodiesel

Properties	Diesel	B10R	B20R	B30R	B40R
Density (kg/m^3)	853	877	878	880	883
Calorific value (kJ/kg)	44755	43800	43000	42100	41200
Kinematic viscosity at 40°C (mm^2/s)	4.0	4.4	4.6	4.8	4.9
Flash point (°C)	70	95	102	112	120

Table 2. Engine Specification

Parameters	Specification
Make	Kirloskar
Output power	5.2 kW
Speed	1500 rpm
Bore X Stroke	87.5 X 110 mm
Compression ratio	17.5:1
Loading type	Electrical dynamometer
Max. Torque	3.5 kgm@1500 rpm

3. ANN Modelling

Neural networks are non-linear computer algorithms and can model the behaviour of complicated non-linear processes. ANNs do not need an explicit formulation of physical relationships for the concerned problem. In other words, they only need examples of the subject in the relevant context. Neural networks are composed of simple elements operating in parallel. These elements are inspired by biological nervous system of the human being. A neural network can be trained to perform a particular function by adjusting the values of the connections called weights between the adjacent elements. The basic processing element of a neural network is neuron. Fundamentally, a biological neuron receives inputs from certain sources, combines them in some way, and performs a generally non-linear operation on the results, and presents them as the output. Such a neuron first forms the sum of weighted inputs given by N=$\sum_{i=1}^{p} Wi + b$ where p and W_i are the number of elements and the interconnection weight of the input vector Xi respectively and b is the bias for the neurons. The method of modifying the weight in the connections between network layers with the objective of achieving the expected output is called training a network The internal process that takes place when a network is trained is called as learning. Neural network operates like a 'black box' model; the user does not need to know any detailed information about the system. On the other hand, they have the ability to learn the relationship between the input and output. The network usually consists of an input layer, some hidden layers and an output layer. Different algorithms are used for training the network. Of them most popular one is online back propagation algorithm which has different variants. The performance of the network outputs are evaluated by a regression analysis between the network outputs and the actual outputs. The criteria used for measuring the network performance are the correlation coefficients, mean relative error. The correlation coefficient assesses the strength of the relation between the predicted and the experimental results and its ranges between -1 and +1. R values close to + 1 indicate a positive relationship.

An ANN model for the biodiesel engine was developed by using the steady state experimental data. In the model 70% of the experimental data were used for the training set, 15% for the validation set and remaining 15% were employed for the test purpose. The inputs to the ANN are blend percentage, brake power (BP), brake specific fuel consumption (BSFC) and exhaust gas temperature. The output parameters from the ANN are brake thermal efficiency (BTE) and emissions which include oxides of nitrogen (NO_x), carbon dioxide (CO_2). Schematic representation of the network input and the output for brake thermal efficiency are shown in Figure 2. The same architecture was used for the other outputs i.e.,

NO_x & CO_2. The number of hidden layer and the neurons within each layer was designed by the complexity of the problem and the data set. In order to ensure that each input provides an equal contribution in the ANN, the inputs of the model were pre-processed and scaled into a common numeric range (-1, 1). To find out the suitable architecture of the network for the present problem, optimization tool in neuro intelligence evaluation software is used. The model with 4-2-1 architecture is found to be the most suitable for the prediction of engine performance and emission characteristics. It consists of 105 neurons in input layer, two neurons in hidden layer, and one neuron in output layer corresponding to brake thermal efficiency, exhaust emissions like oxides of nitrogen and carbon dioxide. The optimized learning rate used is 0.1 and the momentum coefficient used is 0.1. The optimal values of learning rate and momentum coefficient are achieved through optimization tool box in the software used. Using online back propagation algorithm input vectors and the corresponding target vectors from the training set were used to train the network. The output of the network was compared with desired output at each presentation and the error was computed. This error was then back-propagated to the network and used for adjusting the weights such that the error decreases with each iteration. Training will be ceased if the performance goal is met or if the validation error exceeds the training error. Once the training has been ceased the training procedure has approximated a function between the input and output variables and this network may be used for the prediction of unseen data. The details of the architecture used are given in Table 3.

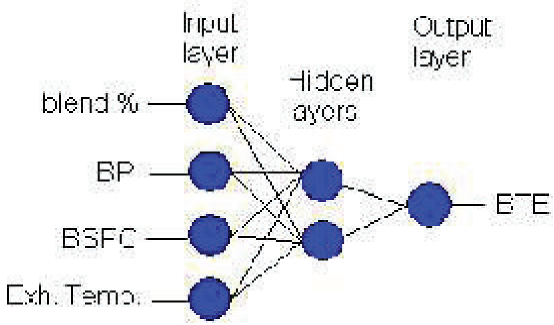

Fig. 2. Neural network architecture for brake thermal efficiency

Table 3. Details of architecture used and results

Parameters	BTE	NO_x	CO_2
Network Configuration	4-2-1	4-2-1	4-2-1
No. of iterations	500	500	500
Absolute error for training	0.8910	24.9	0.1980
Absolute error for validation	0.9184	26.83	0.1730
Training speed, ite/sec	834.99	834.99	834.99
Training algorithm		Online back propagation	
Learning rate	0.1	0.1	0.1
Momentum	0.1	0.1	0.1
R^2	0.9481	0.9855	0.9739

4. Results and Discussion

The aim of this paper is to show the possibility of using the neural network for prediction of engine performance & exhaust emissions. Result shows that, in most of the cases the network produces results parallel to the experimental values; therefore they can be used as an alternative way in these systems. The root mean square (RMS) error values are smaller than 0.02 and coefficient of determination (R^2) values are about 0.999, which may easily be considered within the acceptable values. One deduction made from our experimental results and the prediction produced by ANNs is that, if the experiments are producing steady results (i.e., repeating an experiment under the same conditions produces almost the same results), the usage of ANNs may be highly recommended. To be able to train a neural network, there must be either a logical linear relation or a logical non-linear relation between the input and output.

The trained network was subjected for testing. Mean relative error and the regression analysis was carried out for the trained as well as the test data. Statistical values for the training data and the test data are shown in Table 4. The R^2 values for the training data for BTE, CO_2 and NO_x are 0.9646, 0.9614 and 0.9827 respectively which is very close to unity showing good correlation between the experimental values and network outputs. The mean relative errors (MRE) for the above training set are 1.05%, 1.6% and 3.5% respectively which are within the acceptable limits. For the test data R^2 values for the above parameters are 0.953, 0.9622 and 0.98125 respectively and for the validation data R^2 values are 0.9481, 0.9739 and 0.9855 respectively. Hence there is a strong correlation between the experimental and ANN predicted values. It is very clear from the Figure 3 that the error improvement is closer to zero for BTE. The relation between experimental vs ANN predicted data and scatter plot are shown in Figure 4 (a) & 4 (b). It shows a good statistical performance with the regression values closer to unity and the MRE are within the acceptable limit. Furthermore the figure demonstrates that the ANN target values & experimental output values are closer to each other, hence Artificial Neural Networks can be effectively used for modelling the engine performance parameters and exhaust emissions. Experimental versus ANN predicted results are shown in Table 5.

Table 4 Statistical values of ANN prediction

Parameters	R value			R^2 value		
	Training	Testing	Validation	Training	Testing	Validation
Brake thermal efficiency (BTE)	0.9856	0.9848	0.98	0.9646	0.953	0.9481
Carbon dioxide (CO_2)	0.9830	0.983125	0.9870	0.9614	0.9622	0.9739
Oxides of nitrogen (NO_x)	0.9924	0.9909	0.9927	0.9827	0.9812	0.9855

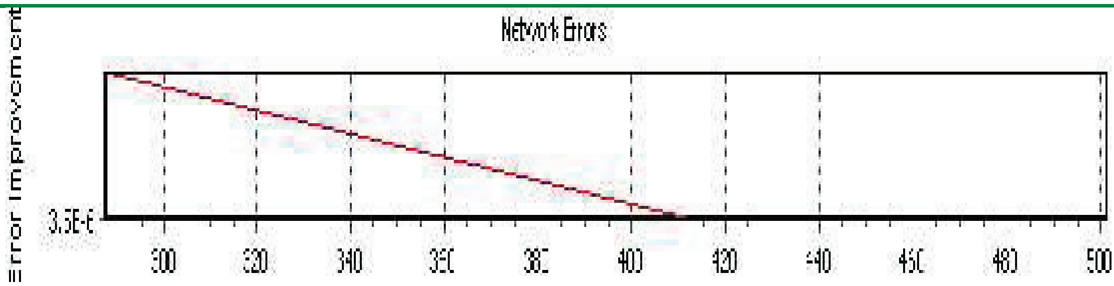

Fig. 3 Network error for brake thermal efficiency

Table 5 Experimental Vs ANN predicted values

Parameters	Training		Testing		Validation	
	Target	Output	Target	Output	Target	Output
BTE (%)	5.41	5.68	7.28	6.99	8.88	8.84
	24.93	24.35	23.84	23.83	24.79	24.26
NO_x(ppm)	209	204.97	191	195.3	177	183.44
	825	827	804	808.66	753	746

CO_2 (%by vol)	3.2	3.019	2.8	2.93	2.7	2.95
	6.8	6.43	6.0	6.03	6.3	6.14

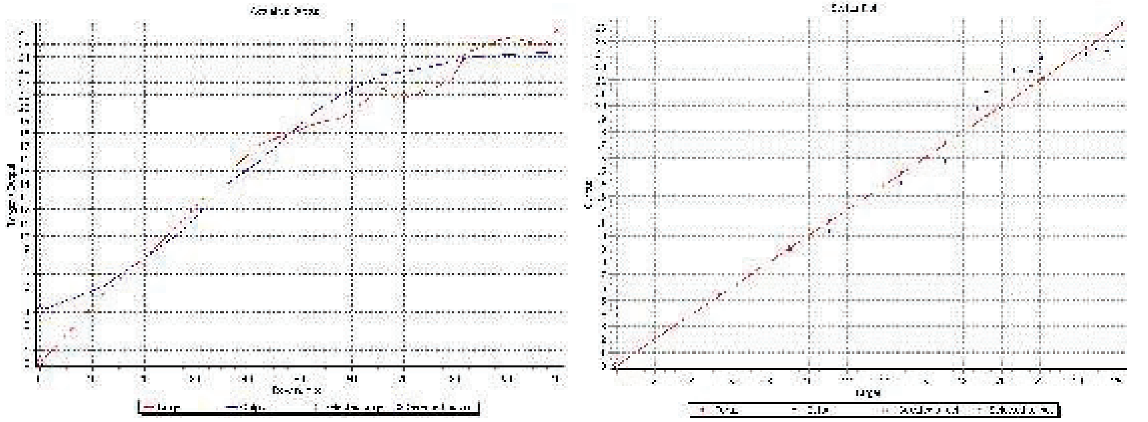

Fig. 4 Experimental vs ANN predicted validation network output for BTE; (b) Scatter plot for BTE

5. CONCLUSION

Experiments were conducted for the analysis of performance and emission of diesel engine operated on rapeseed oil based biodiesel. The parameters considered for the experimentation was brake power, blend percentage, exhaust gas temperature and specific fuel consumption. Online back propagation ANN model was developed. Based on this investigation, the following conclusions are drawn:

- Neural network configuration is optimized and 4-2-1 structure was selected for the training of 105 data sets. Using the weights obtained during training, fresh data sets were tested and the solutions obtained by the ANN are validated with that obtained by experimental values. The number of test data used in this work is only limited. The increase in test data will improve the result further.
- ANN approach applied to predict the performance and emission characteristics provides satisfactory results with the regression coefficients lying closer to 1 and mean relative error is within less than 5% for the entire test data which is considered to be within the acceptable limit.
- The specific fuel consumption is slightly higher for B20R, but closer to diesel among all the blends. When the concentration of rapeseed oil methyl ester is more than 20% by volume, there is an appreciable increase in the specific fuel consumption.
- Increase in NO_x emission was observed for biodiesel blends compared to that of diesel.
- CO_2 emissions decreased as the bio-diesel content increased. This result is very important because CO_2 is the primary green house gas contributing to global warming.

On the whole it is concluded that ANN approach can be used for the prediction of performance and emission characteristics of I.C engines by performing a limited number of tests instead of detailed experimental study thus saving both engineering effort and funds.

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