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Original scientific paper

Study and Optimization of Ethanol (LRF) Juliflora Biodiesel (HRF) Fuelled RCCI Engine with and without EGR System

Manivannan RAMACHANDRAN*, Neelakrishnan SUBRAMANYAN

Abstract: Over the past few decades, the use of non-renewable energy has progressively expanded, harming the environment. In this investigation, 4-stroke single-cylinder Reactivity Controlled Compression Ignition (RCCI) engine performance and emission behaviour are reduced with the help of running fuel. 20% Juliflora biodiesel and 80% diesel are used as high-reactive fuel (HRF) and Ethanol is used as the low-reactive fuel (LRF). The RCCI engine is evaluated at different input conditions by varying engine load from 0 to 100 (0, 25, 50, 75, and 100%) and LRF percentage from 30 to 60 (30, 40, 50 and 60%). Additionally Exhaust Gas Recirculation (EGR) is used to enhance the RCCI engine emission behaviour and performance.The studied output performance of RCCI engine are cylinder pressure (CP), brake thermal efficiency (BTE), heat release rate (HRR), and brake-specific fuel consumption (BSFC) respectively. Also, unburned hydrocarbon (HC), carbon monoxide (CO), nitrogen oxides (NO_X), and smoke opacity (SO) are calculated on the RCCI engine for all input condition. The test results are further optimized with the help of hybrid deep belief neural network based Aquila optimization method. The proposed hybrid DBN-AO has performed better than conventional DBN method.The predicted optimal value is obtained from the regression and average regression coefficients of 0.99961. The predicted optimum values are load 80%, LRF60%, and EGR 15%, respectively. The confirmatory error analysis has shown BTE (3.7%), BSFC (4%), SO (4.7%), HC (7.775%), CO (3.44%) and NOx (3.46%) respectively. The EGR application reduces the RCCI engine emission behaviour in loading condition.

Keywords: aquila optimization; deep belief neural network; ethanol; exhaust gas recirculation; juliflora biodiesel; reactivity controlled compression ignition

1 INTRODUCTION

It is estimated that the Global population growth, that is increasing day by day, is likely to reach 8.5 billion by 2030 and 11.2 billion by 2100. The large population expansion is pointing to the high amount of energy consumption and necessity. Population growth necessitates the use of more energy to meet basic needs such as cooking, lighting, and transportation etc. More than 80% of the energy used globally at the moment comes from traditional sources. The automotive sector is one of the top energy consumers globally compared to any other sector where Oil plays the main role. The demand for fuels is rising while the amount of crude oil available is decreasing. The availability of crude oil affects not just the transportation sector but also the agricultural and industrial ones. High demand and high consumption will lead to a sharp rise in crude oil prices in the current scenario. The demand for diesel in India is five times greater than that for gasoline since it is mostly used in the transportation sector [1].

2 RELATED WORKS

Several authors have attempted to replace diesel fuel with biodiesel extracted from various edible and non-edible oils. Vegetable oil-based biodiesel has drawn researchers' attention over the past three decades as a potential replacement for conventional fuels [2]. The performance of juliflora-based biodiesel with the help of a direct injection engine (DI) diesel engine. The DI diesel engine's combustion and emission behaviour were evaluated, and the test result indicated that 20% of juliflora-based biodiesel delivered better performance [3]. Rajamohan et al. [4] analysed the engine performance, oxidation stability, and combustion behaviour of juliflora-based biodiesel. 20% of biodiesel in 80% diesel improved the thermal and emission characteristics. Similarly, the existing author has identified castor oil and rice bran oil as reliable sources for biodiesel production [5, 6]. The performance of biodiesel (cottonseed oil) blended with additives was analysed using a self-designed droplet combustion [7].

The traditional combustion engines are producing large amount of emissions, and at the same time, while modern-day emission regulation is strong [8]. Due to such stringent emission regulation, the low temperature combustion (LTC) engine is more popular than the traditional engine. The LTC is running on the dual fuel mode, namely low reactive fuel and high reactive fuel (HRF), for example, reactivity controlled compression ignition (RCCI) [9]. In the RCCI engine, low-reactivity fuel (LRF) such as gaseous fuels is allowed through the intake manifold along with the air. Similarly the high-reactivity fuel such as diesel and other similar forms of diesel fuel is directly injected into the cylinder at the end of compression [10].

Elkelawy et al. [11] have reviewed the impact of exhaust gas recirculation (EGR) on reactivity-controlled compression ignition engines management. The author concluded that the high exhaust gas recirculation reduced soot and NO_X at maximum loading condition. Elkelawy et al. [12] have evaluated the combustion, efficiency, and emission behaviour of an EGR-integrated RCCI engine. The EGR ratio varied from 10% to 30% as a result, the level of emitted NO_X was reduced in the EGR integrated RCCI combustion process. Zheng et al. [13] investigated the performance of dual-fuelled RCCI with different EGR ratio varied (0 %, 30% and 50%).

Recently, the researchers optimised the engine performance with the help from response surface methodology (RSM) and a hybrid optimization method (Deep Recurrent Neural Network based Honey Badger Algorithm) [14, 15]. Hybrid ANN (artificial neural network) with the fuzzy approach was used to optimized the CI engine [16, 17].

As for the literature, the RCCI engine-based research is very limited, therefore in this investigation, the RCCI engine is used and its performance is analysed for juliflora biodiesel (used as HRF in this study) with different LRF procedures. Besides, the literature identified with efficiency optimization techniques such as RSM, ANN, and DNN for RCCI engine optimization; in this sense, a novel optimization algorithm called Aquila optimization (AO) algorithm is used to achieve extended prediction and optimization accuracy from deep belief neural network (DBN). The article is structured as follows: the details on materials and methodology used in this study are provided in section 3. The study conclusion is in section 5, while section 4 covers experimentally obtained, DBN-AO predicted, and optimum results.

3 MATERIALS AND METHODOLOGY

The performance and emission characteristics of RCCI-based single-cylinder engines are determined in this study by using various fuel blends.To run the engine in RCCI mode, the engine has been precisely changed as shown in Fig. 1.

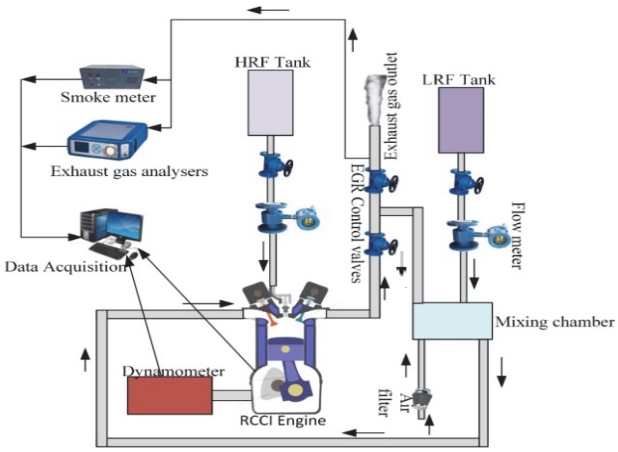

Figure 1 Diagram of the RCCI engine's experimental configuration with the EGR system

In general, the RCCI engine operates by utilizing two distinct fuels namely LRF and HRF. Since the calorific value plays a major role in the RCCI engine's performance, biodiesel synthesized from juliflora feed stock has shown significant improvement in terms of calorific value over other existing biodiesel feed stocks [18]. Besides, the literature evidences that using 20% juliflora biodiesel mixed diesel fuel results in less greenhouse gas emission [3, 4]. Therefore, 20% juliflora biodiesel and 80% diesel blend is used as HRF in this study. Similarly, ethanol is used as LRF in order to achieve minimum emission with improved efficiency based on literature review [19, 20]. The intake valve of the RCCI engine is modified by installing a mixing chamber, which allows for LRF-mixed fresh air and EGR. The EGR system lowers combustion temperatures and thereby reduces the quantity of emission released by returning a small part of exhaust gas to the engine's combustion chamber through the intake manifold. One end of EGR inlet valve is connected to the RCCI engine exhaust while the other end is connected to the mixing chamber where the EGR is mixed with pure air. Also, the control valve is used to control the EGR flow level. The exhaust path is connected to the exhaust gas analyser and smoke meter. The photograph of RCCI engine experimental setup with the EGR system is shown in Fig. 2.

Figure 2 RCCI engine experimental setup

In this study, the AVL Austria, model: 444 Digasgas analyser having specifications mentioned in Tab. 1 is used to evaluate the emission behaviour of RCCI engine such as carbon monoxide and unburned hydrocarbon, NO_X. Similarly, RCCI engine smoke opacity is evaluated with the help of AVL 437 smoke meter for all experimental conditions. The specification of smoke meter used in this study is given in Tab. 2.

Table 1 Specification of exhaust gas analysers

Exhaust gas	Measurement range	Resolution	Accuracy
CO	0-10 vol%	0.01 vol%	< 06%. ± 0.03% vol. 0.6Vol ± 5% ofind.val
HC	0-20000 ppm	> 2000:1 ppm 2000 ppm-vol. ± 10 ppm	< 200 ppmvol. ± 10 ppmvol. 200 ppmovol. ± 5% ofind.val
NO_X	0-500 ppm	1 ppm vol	< 500ppmvol. ± 50 ppmvol 500 ppmvol. ± 10% ofind.val

Table 2 Specification of smoke meter

Measurement principle	Measurement of filter paper blackening
Measured parameters	Filter smoke number, soot concentration
Measurement range	0-10 FSN
Exhaust pressure range	~100 to 400 mbar
Maximum exhaust temperature	600 °C with standard 340 mm probe
Power consumption	700 VA
Dimensions	560 × 620 × 300 mm

The ethanol storage container is connected to the mixing system with the help of a pipe line. Ethanol entering the mixing unit is controlled by a control valve and monitored by an ethanol flow control meter. Filtered atmospheric air enters the mixing chamber, and air flow is measured using an air flow meter. In the mixing chamber, the air and LRF are mixed properly, and the percentage of LRF added is also varied (30%, 40%, 50%, and 60%). The mixing chamber outlet is linked to the RCCI engine air intake valve, which supplies air, ERG, and LRF. The bio-diesel is stored in the HRF storage tank, and the tank valve is linked to the RCCI engine fuel intake. The HRF flow is controlled by the HRF valve, and the flow is monitored by the flow meter, which regulates the HRF flow.

The dynamometer is connected to the engine, which helps to measure engine performance like torque and power. In addition, the sensor measures the temperature and pressure produced by the engine. The Engine software is used to evaluate the overall efficiency of the RCCI engine under various loading and input conditions. The overall engine specification and sensor list are discussed in Tab. 3. With the help of data acquisition, all input and output, including sensor data, are collected. This investigation is primarily focused on measuring the cylinder pressure (CP), heat release rate (HRR), brake thermal efficiency (BTE), and brake specific fuel consumption (BSFC). Similarly, the RCCI engine emission section includes carbon monoxide (CO), unburned hydrocarbon (HC), nitrogen oxide (NOX), and smoke opacity (SO).

Table 3 Specification of RCCI engine

Engine code	240PE
Engine	Diesel: power 3.5 KW, speed 1500 rpm,CR range 12;1-18;1.injection variation:0-25 Deg BTDC Specification: 4 stroke single cylinder engine, capacity 661cc, bore 87.5 mm, water cooled
Dynamometer	eddy current
Fuel tank	Capacity 15 lit, type:duel compartment
Piezo sensor	Combustion: range 5000 PSI, with low noise cable. Diesel line: range 5000 PSI, with low noise cable.
Crank angle sensor	Resolution 1 Deg, speed 550 rpm with TDC pulse.
Data acquisition device	NI usb-6210,16bit,250kS/s
Engine control hardware	Fuel injector, fuel pump, ignition coil, idle air
Temperature sensor	RTD, PT100 and thermocouple
Load indicator	Digital range 0-50 kg, supply 230 VAC
Load sensor	Load cell, type strain gauge, range 0-50 kg
Software	Enginesoft engine performance analysis
ECU software	Pe Monitor &pe viewer software

Experimental Procedure

The RCCI engine's compression chamber is initially filled with LRF, and the HRF is injected toward the end of the compression stroke at a recommended compression ratio of 16:1 [21]. This dual-fuel procedure helps the fuels burn thoroughly inside the combustion chamber. The prepared LRF and HRF are tested in the RCCI engine, and the efficacy evaluation is conducted under different loading and input conditions. The details of the single-cylinder, four-stroke diesel engine employed in this experiment are shown in Fig. 1. In this investigation performance and combustion behavious are evaluated at five different types of loading conditions and two different types of investigations are conducted with varying input conditions. The first stage is an EGR-free condition, in which the EGR valve is closed and only LRF enters the mixing section. The loading levels are 0, 25, 50, 75, and 100%, respectively, and the LRF ratios are 30, 40, 50, and 60%. The obtained performance and emission behaviour are compared with diesel and biodiesel without LRF condition. The second stage is an EGR condition, in which the EGR valve is opened and LRF enters the mixing section. EGR is added to the mixing chamber with LRF in percentages of 10%, 15%, 20%, and 25%.

Uncertainty Analysis

Environmental variations, equipment calibration errors during observation, and human error are all potential sources of experiment uncertainty. As a result, as indicated in Tab. 5, the uncertainty research was carried out in this work for each measurement. The overall uncertainty is evaluated with help of Eq. (1) and includes sensor errors [22].

$T_1, T_2, T_3, T_4, T_5, T_6$, and T_7 denote the uncertainty of engine speed, Sensors, Heat release rate, Cylinder pressure, Smoke opacity, Carbon monoxides, and unburned hydrocarbon respectively. Similarly, $T_8, T_9, T_{10}, T_{11}, T_{12}$, T_{13}, and T_{14} are represented by the uncertainty of the nitrogen oxides, Thermocouples, Crank angle encoder, Load indicator, Smoke meter, Brake thermal efficiency, and brake specific fuel consumption respectively.

$$Total \quad Uncertainty = \sqrt{\sum_{x=1}^{14} (T_x)^2} \tag{1}$$

$$Total \quad Uncertainty = \pm\sqrt{\begin{matrix}(T_1)^2+(T_2)^2+(T_3)^2+(T_4)^2+(T_5)^2+(T_6)^2+ \\ +(T_7)^2+(T_8)^2+(T_9)^2+(T_{10})^2+(T_{11})^2+(T_{12})^2+ \\ +(T_{13})^2+(T_{14})^2\end{matrix}} \tag{2}$$

$$U = \pm\sqrt{\begin{matrix}(0.2)^2+(0.1)^2+(0.5)^2+(0.1)^2+(0.4)^2+(0.3)^2+ \\ +(0.15)^2+(0.1)^2+(0.1)^2+(0.15)^2+(0.2)^2+ \\ +(0.15)^2+(0.3)^2+(0.55)^2\end{matrix}} \tag{3}$$

$$U = \pm 1.039$$

This study's calculated total uncertainty is ±1.039, which is less than the allowed threshold (±5). As a consequence, the experimental results are trustworthy for real-time applications.

Hybrid DBN-AO Based Predication Optimization

Using neural network methodologies, the experimentation cost of biodiesel optimization was greatly lowered. In this study, a novel hybrid deep belief neural network based Aquila optimization method (DBN-AO) was used to predict and optimize the features of RCCI engine. However, specifically the different LRF, HRF levels, with and without EGR condition. The AO algorithm is applied in DBN as weight optimizer to improve training efficiency. The reason for choosing AO as weight optimizer for DBN is because of its outstanding optimization performance over existing optimization algorithms such as particle swarm optimization, equilibrium optimizer, grey wolf optimizer, ant lion optimizer, etc., Also, the mathematical model of AO consists of both expanded as well as narrowed exploration and exploitation techniques to solve complex calculations to achieve high efficiency in the best or optimum engineering solutions. The DBN-AO structure typically consists of three levels: input, output, and hidden layers. There is a link between the neurons in hidden and visible input layers, but not between the neurons inside the hidden and visible layers. Fig. 3 and Tab. 4 provide an outline of the DBN-AO model and its explanation. The hybrid DBN-

AO inputs are EGR, LRF, HRF, load and the outputs are BSFC, BTE, CP, HRR, CO, HC, SO, and NO_X. The output of each input neuron of the deep belief network (DBN) model was calculated using the Boltzmann network.

Training and Testing of DBN and Hybrid DBN-AO

In this study, experimentally obtained dataset is used to test and train the developed DBN-AO neural network model. The optimization algorithm was trained and tested with a ratio of 3:1, and DBN and hybrid DBN-AO were trained using approximately 75% of the test data. Similarly, DBN and hybrid DBN-AO were tested with approximately 25% of the data obtained in the experiment.

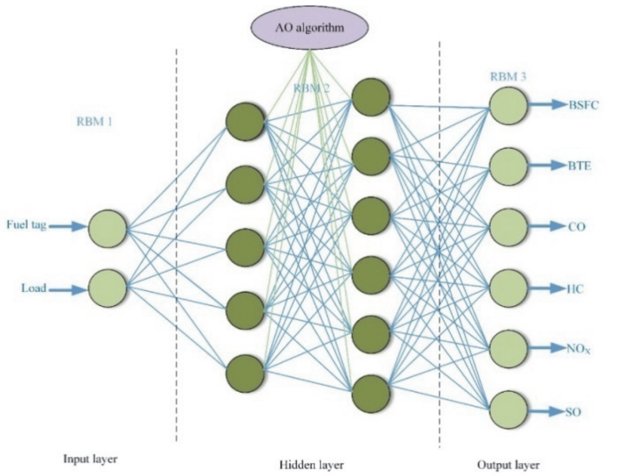

Figure 3 General structure of developed DBN-AO

Table 4 Discretion of DBN and AO

Elements	Specifications
Input and output layer	one
Input and output nodes	2 and 6
Hidden layers	two
Weight updating method	Aquila Optimization algorithm
Learning algorithm	Restricted Boltzmann Machines and Back propagation
Learning rate	0.01
Transfer function	Sigmoid
Maximum number of iterations	1000

4 RESULTS AND DISCUSSION

In this experiment, the RCCI engine heat release rate, combustion, and emission behaviour are evaluated under different LRF, HRF, EGR, and loading conditions. The collected experimental results for each test fuel mix were evaluated side by side in the following manner:

Cylinder Pressure and Heat Release Rate

RCCI engine heat release rate and cylinder pressure were compared with respect to the crank angle in the first stage without EGR condition based on different loading and input conditions. Comparing diesel performance with different loading conditions (25%, 50%, 75%, and 100%) and evaluating different input LRF percentage such as 0%, 30%, 40%, 50%, and 60%. In the RCCI cylinder pressure and heat release rate are clearly shown in Fig. 4. After top dead center (TDC), the greatest or peak pressure was noted between 362° and 368°. At 20% load, the pure diesel's CP rises rapidly when compared to other fuel combinations. Maximum CP is achieved with 50% load condition 60% LRF. According to Fig. 3, the load plays an important role in CP. If the load increases, CP increases gradually for the prepared LRF and HRF fuel intake. A maximum of 56.329 bar CP is achived for a 25% loading condition, whereas CP is further increased to 64.684 bar at a 100% loading condition. The maximum HRR is achieved in all loading conditions at a crank angle of 360° to 365°. This fall in HRR is mainly due to the lower calorific value of LRF and HRF blend. In the compression process, compared to fuels with a higher calorific value, fuels with a lower calorific value produce less heat when burned. 50% LRF achieves maximum HRR when compared to other combinations at 20% loading levels. Higher HRR is achived at 50, 75 and 100% load with 60% of LRF. 56.171 J/degree HRR is achived in the 25% load condition, and 56.453 J/degree HRR is achived in the 50% load condition. Load plays an important role in HRR, and the load increases the HRR.

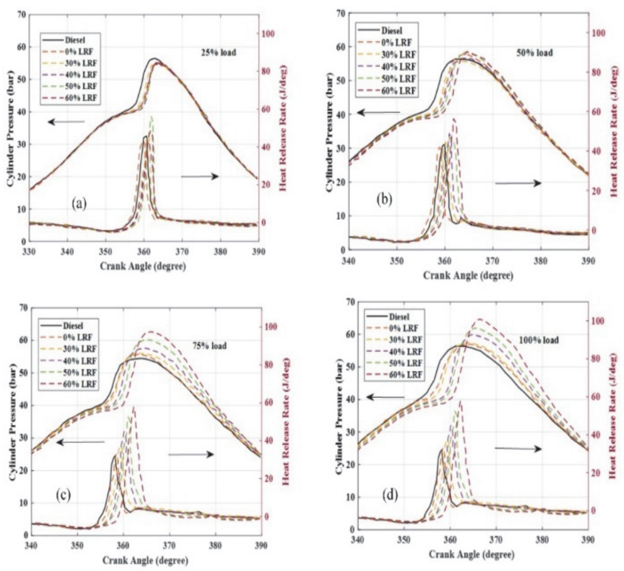

Figure 4 RCCI engine cylinder pressure and heat release rate at different loading conditions

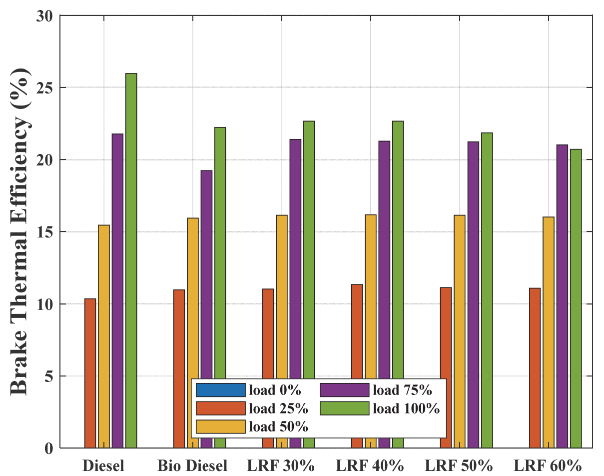

Figure 5 RCCI engine brake thermal efficiency at different loading conditions

Fig. 5 shows the BTE for the chosen mixtures under various loads. Generally, the high oxygen content is improving the RCCI engine's combustion performance. The BTE is being improved by the prepared LRF and HRF combination when compared to diesel and biodiesel, as indicated by the test results. The main factor influencing the RCCI engine's BTE performance is the load. The BTE increases when the load increases, and it gradually decreases when the load decreases. The maximum BTE is obtained in the 30% load condition LRF 30%, while the minimum amount of BTE is obtained in the 25% load condition. All fuel combination the maximum BTE is obtained by the 100% loading condition. gradually in the prepared LRF and HRF composites.

Brake Thermal Efficiency

LRF 60% fuel based operation gives lower BTE (20.12%) at 100% loading condition and slightly higher BTE (21.852%) at 75% loading condition compared to 100%.

Brake Specific Fuel Consumption

Fig. 6 illustrates the changes in Brake Specific Fuel Consumption (BSFC) of the RCCI engine when operating with different LRF ratios and pure diesel fuel for variable loads. Lower caloric value of fuel increases BSFC, and as the load increases, it gradually decreases. The lowest BSFC is achieved in diesel under 0% load condition, while the highest is achieved in 100% load condition. For all fuel combinations, the maximum BSFC is obtained at 100% loading condition.

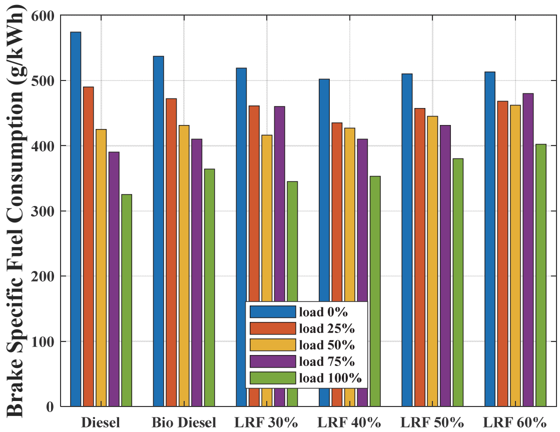

Figure 6 RCCI engine brake specific fuel consumption at different loading conditions

The test results indicate that the prepared LRF and HRF combination is improving the BSFC when compared to diesel and biodiesel. The BSFC decreases when the load increases and it gradually increases when the load decreases. The maximum BSFC is obtained in the 30% load condition with 30 % LRF, while the minimum amount of BSFC is obtained in the 25% load condition. In all fuel combinations, the minimum BSFC is obtained by the 100% loading condition. LRF 30% fuel based operation gives higher BSFC (345 g/kWh) at 100% loading condition and diesel gives the maximum BSFC (574 g/kWh) in 0%. Similarly, the minimum amount of BSFC (502 g/kWh) level at LRF 40% is specified at 0% loading condition.

Exhaust Gas Emission Analysis with Different Proporions of Fuels:

The test result is shown in Fig. 7, and it compares the exhaust gas emissions at different combinations of LRF. The maximum CO (0.05%) is obtained in diesel with 100% load condition, while the minimum amount of CO (0.04%) is obtained in the 0% load condition in bio-diesel. For all fuel combinations the maximum CO is obtained by the 100% loading condition. The minimum CO is obtained in the 0% loading condition in LRF. Fig. 7c displays the HC emission and compares the outcomes of various loading conditions. When the RCCI engine is driven by diesel, the HC level increases gradually, especially as the load increases, but it decreases from 20% to 0% load. The maximum HC (37 ppm) is obtained in the 100% load condition with diesel, while the minimum amount of HC (LRF 30% = 19 ppm) is obtained in the 25% load condition in LRF. The RCCI engine smoke opacity is measured at different loading conditions, as shown in Fig. 7b. The smoke opacity emission rate reduced gradually as load increases; this indicates that the fuel is burning clearly. The 60% LRF shows the lowest NO_X emission for loading conditions above 25%. As a result, 60% LRF is selected as suitable LRF condition for further experiments on different EGR percentages in this study.

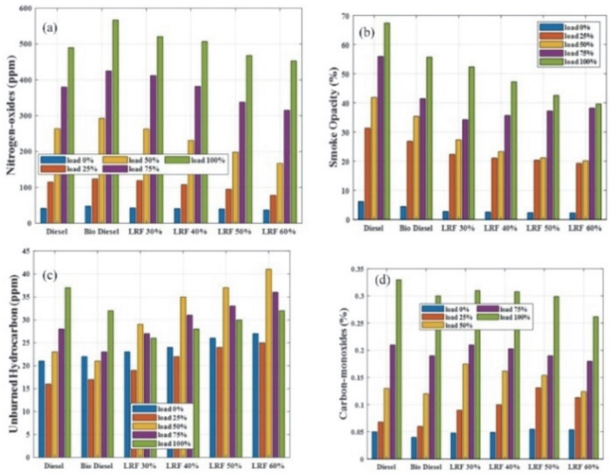

Figure 7 RCCI engine emission behavior at different loading conditions

Exhaust Gas Emission Analysis of Different EGR Condition

Fig. 8a illustrates the carbon monoxide emissions percentage with different EGR and LR conditions. The maximum NO_X is obtained in the 100% load condition with diesel, while the minimum amount of NO_X is obtained in the 0% load condition. All fuel combination maximum NO_X is obtained by the 100% loading condition. The test result clearly shows that EGR reduces NO_X emissions and outperforms diesel and LRF by 60%. The percentage of EGR reduces NO_X emissions, especially as it gradually decreases with increasing load conditions. The combustion performance of the RCCI engine with LRF and HRF is being improved by the EGR, as indicated by the NO_X reduction. Fig. 8b illustrates the carbon monoxide emissions percentage with different EGR and LRF conditions. The minimum CO is obtained in the 0% loading condition with and without EGR. It should be noted that CO emissions increase steadily after LRF 60% + 15% EGR at 25% load, demonstrating that EGR has an effect on the combustion process. Fig. 8c illustrates the unburned hydrocarbon emissions percentage with different EGR and LRF conditions. The test result clearly indicates the EGR is reducing the HC emission but not beating the diesel and LRF 60 %. Fig. 8d illustrates the emission smoke opacity percentage with different EGR and LRF conditions. The test result clearly shows that EGR reduces SO emissions and equal to the diesel. The percentage of EGR reduces SO, especially as it gradually decreases with increasing load conditions. The combustion performance of the RCCI engine with LRF and HRF is being improved by the EGR, as evidenced by the SO reduction. Overall, as per the emission results presented in Fig. 8, the RCCI engine, which operates with 60% LRF and EGR up to 15%, could provide the desired emission control, which is within the range of Bharat Stage-VI (BS-VI) emission norms at lower loading conditions. In contrast further increase in EGR % will lead to higher levels of CO and HC emissions. Therefore, 15% EGR substitution is suggested for the proposed 60% LRF and HRF (20% Juliflora biodiesel + 80% diesel blend) fuelling conditions of RCCI engine.

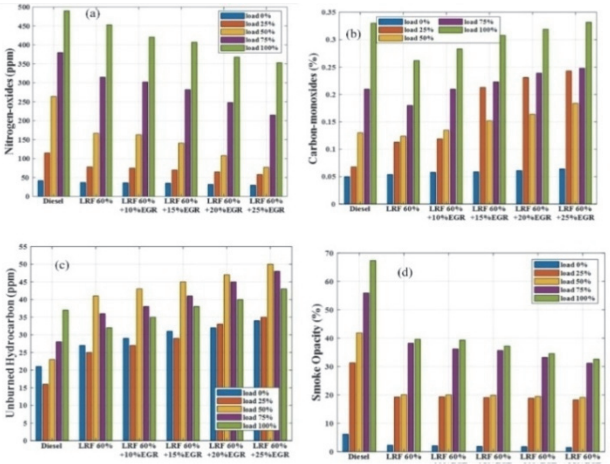

Figure 8 RCCI engine emission behavior at different EGR conditions

Prediction and Regression

The optimisation algorithm is trained and evaluated to find the best prediction; this is compared with the experimental result. The hybrid DBN-AO is compared with DBN prediction result, which concludes that the hybrid DBN-AO is closely predicting the experimental result. The regression is used to find the accuracy of DBN-AO's predictions, based on the actual result. The regression for engine performance is shown in Fig. 9 (a and b) and the regression for the emission characteristics of the engines is shown in Fig. 10 (a, b, c and d).

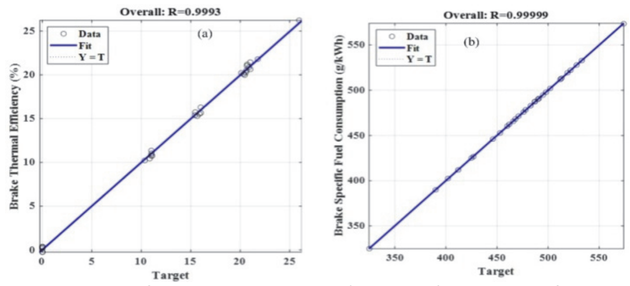

Figure 9 Combustion prediction performance of hybrid DBN-AO

Confirmatory Experiment

In this investigation, a confirmatory test is conducted to find the error or defence of the obtained result. The confirmatory test result is shown in Tab. 5, and it includes deviations from the predicted and experimental values. The optimal performance and emission behaviour are obtained with the LRF fuel type condition of 60% + 15% EGR and the 80.23% load condition. The optimum BTE and BSFC are 20.983 % and 448 g/kWh, respectively, and obtained errors (%) are 3.7 and 4. The optimum Smoke opacity, CO, HC and NO*x* are 36.12% 0.261%, 40 ppm and 318 ppm, respectively are obtained at 4.7, 3.44, 7.775, and 3.46% error.

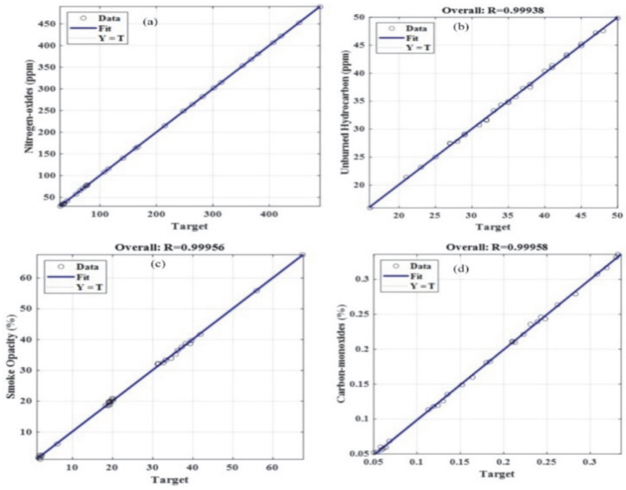

Figure 10 Emission prediction performance of hybrid DBN-AO

Table 5 Confirmatory test

Engine characteristics	Optimal value	Confirmatory value	Error / %
Load / %	80.23	80	0.286
Fuel type	LRF 60% + 15% EGR	LRF 60% + 15% EGR	-
BTE / %	20.983	20.188	3.7
BSFC / g/kWh	448	468	4
Smoke opacity / %	36.12	37.28	4.7
CO / %	0.261	0.270	3.44
HC / ppm	40	43.11	7.775
NO*x* / ppm	318	329	3.46

5 CONCLUSION

In this investigation the RCCI engine performance is evaluated with the help of different LRF, HRF and EGR in different loading condions. The obtained performance and emission behaviour are summarized below: the maximum performance is achived at 100% loading condition in all LRF conditions. Maximum CP is achieved by 60% of LRF in 50% of loading conditions, and minimum CP is achieved by 60% of LRF in 75% of loading conditions. The maximum BTE is obtained in the 30% load condition LRF30%, while the minimum amount of BTE is obtained in the 25% load condition. All fuel combination the minimum BSFC is obtained by the 100% loading condition. LRF 30% fuel-based operation gives higher BSFC (345 g/kWh) at 100% loading conditions, and diesel obtains the maximum BSFC (574 g/kWh) at 0%. The smoke opacity emission rate reduces gradually as load increases; this indicates that the fuel is burning clearly. The EGR and without EGR test results are compared and the test data show the EGR is reducing the RCCI engine's exhaust emissions. The EGR is reducing the RCCI engine NO_X and CO in all loading conditions in such a way that if the load is increased the NO_X and CO emission is gradually reduced. Besides, the hybrid DBN-AO prediction result is compared with the experimental results, and over 99% overall prediction accuracy is achieved. Also, the optimum conditions of 60% LRF + 15% EGR and 80.23% load is obtained from the proposed optimization model. Further the confirmatory analysis show BTE, BSFC, SO, HC, CO and NO*x* are 2.188%, 468 g/kWh, 37.28%, 43.11 ppm, 0.270% and 329 ppm respectively. Finally, the experiment resulted 15% EGR and 60% LRF substituted RCCI engine could maintain lower NOX, CO, smoke and HC emissions with marginal compromise in BTE than normal diesel. Thus, the study may help in the future improvement of Bharat Stage (BS) emission norms. However, the experiments in this study are conducted at a constant compression ratio of 16:1, but there is scope for further enhancement of results by manipulating the compression ratio of the RCCI engine fuelled with the proposed fuel combinations. Also, various LRF fuels such as, gasoline, compressed natural gas, and other alcohol fuel additives can be tested and compared with the proposed study for accademic purpose.

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Contact information:

Manivannan RAMACHANDRAN, Head of the Department
(Corresponding author)
Department of Automobile Engineering,
Nachimuthu Polytechnic College, Pollachi
E-mail: manivanan.r134@yahoo.com; manivanan.r134@gmail.com

Neelakrishnan SUBRAMANYAN, Professor
Department of Automobile Engineering,
PSG College of Technology, Coimbatore
E-mail: neelpsg@gmail.com