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Performance Analysis of Dual Biodiesels of Pongamia and Cotton Seed Oils and Numerical Analysis of BTE and BSFC

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Abstract*: Blending diesel with vegetable oils has gained tremendous scope for conventional energy recourses in automobiles. There has been lot of work done on biodiesel and is still a topic of interest among scientific community in alternative fuels. Very few works have been reported with the mixing of two different biodiesel blends with diesel and leaves a lot of scope in this area. This paper deals the experimental and numerical analysis of dual bio diesel. Experiments were conducted with mineral diesel and bio diesel blends of pongamia oil and cotton seed oil at different blending ratios (B10 = 10% of biodiesel, B20 = 20% biodiesel, B30 = 30%) on a single cylinder VCR diesel engine. The performance of dual biodiesel blends were investigated in terms of break power vs break thermal efficiency and break specific fuel consumption. The brake thermal efficiency of blends B10, B20 and B30 were found higher than diesel, and brake specific fuel consumption of all the bio diesels are lower than mineral diesel. An attempt was made to create a mathematical model of BTE vs. engine torque and engine speed; and BSFC vs. engine torque and speed by the means of regression analysis using the observed data for studying the effect of the fuel heating value and the brake thermal efficiency (BTE). The developed mathematical model closely correlates with experimental observations. We conclude that designed BTE and BSFC contour's gives a range of torque and speed of VCR diesel engine on which it can be operated effectively.

***Index Terms*: BSFC, BTE, Dual biodiesel, Cotton seed oil, Pongamia oil, Numerical analysis.**

I. INTRODUCTION

Energy is one of the most crucial factors that influence the consistent development and economic growth of a country. With the day by day increase in the demand for energy and the depletion of conventional energy resources, there arises a need for alternative energy resources that will not also cause pollution. This motivated the researchers to focus on sustainable, renewable, biodegradable and eco-friendly technologies. These technologies have to run on renewables or what can be called as alternate fuels. In recent times, to replace the existing fuels, utilization of alternative fuels such as biodiesel in diesel engines in automobiles has become prevalent due to exhaustion of petroleum-based diesel fuel [1], [2]. Diesel consumption is prevalent among various groups of consumers as the engines that run on them are efficient and consume very less amount of fuel. Though this adds to the benefits, on the flip side, the consumption of diesel produces different sets of emissions and causes pollution. Since the consumption is on a higher note; their exhaustion is another problem, besides the increase in the corresponding price. Hence, either these resources should get replenished, or an alternative has to be found out that would meet all the requirements [2]. Various alternatives are being developed and being tested upon.

Among the alternative fuels, biodiesel is one on which researchers are focusing more to make it a viable alternative. Biodiesel is primarily derived from different vegetable oils, animal fats and constitutes of mono-alkyl esters of long chain fatty acids. Biodiesels are non-toxic and are rapidly biodegradable. They have a higher flash point when compared to the conventional diesel. It has the advantage of being eco-friendly, releases less NO_x and hydrocarbons, absolutely no SO_x and less CO_2, when used in different blend ratios with diesel. Since biodiesels emit less CO_2, it turns out to be a carbon neutral product [2], [3].

Several studies demonstrate the usage of single biodiesels in diesel engine [1] – [4]. However, only a few studies have focused on the usage of dual biodiesels in diesel engine [5] – [8]. Dual biodiesel fuel involves blending any two biodiesels with diesel, thereby providing the advantages of both the biodiesels. Srithar *et al*. [5] conducted experiments on CI engine using pongamia oil and mustard oil with diesel and studied the performance of diesel engine and exhaust emissions. They concluded that thermal efficiency and mechanical efficiency of 'blend A' (Diesel 90%, pongamia oil 5% and Mustard oil 5% by volume) was slightly more than that of diesel. The specific fuel consumption values of dual biodiesel blends were comparable to diesel. Blend A, and Blend B (Diesel 80%, pongamia oil 10% and Mustard oil 10% by volume basis) and CO_2 than diesel. The dual biodiesel blends gave higher smoke opacity, HC and NO_x than diesel.

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Prabhakar *et al*. [6] studied the performance of pongamia and madhuca oils on the diesel engine and found that 20% hybrid vegetable oil and 80% diesel can be used to replace diesel without modifying the diesel engine with less power loss, and less emission of Hydrocarbons (HC) and CO. Rao [7] conducted the experiments on CI engine with dual biodiesels of pongamia and jatropha along with diesel. The results show that performance of D90PJBD10 (Diesel 90%, pongamia and jatropha 10%) and D80PJBD20 (Diesel 80%, pongamia and jatropha 20%) were very close to that of diesel, and emphasize that diesel can be replaced with pongamia and jatropha. Nalgundwar *et al*. [8] successfully run a single cylinder CI engine with dual biodiesel blends of Jatropha and palm. Dubey *et al*. [9] found that the blends of Jatropha biodiesel and turpentine (JBT50) show superior emission and performance than stranded diesel and other dual biofuel blends at full load and compression ratio of 20:1.

Lower blends of dual biodiesel can be used as an alternative to diesel oil without changing the design of the engine. Since very less work has been done in the area of dual or hybrid diesel blends, it shows more scope in the area of alternative fuel development. Both pongamia and cottonseed oil are available easily and are cheaper than diesel. Hence, this study attempts to investigate the feasibility and performance of dual biodiesel blends of pongamia and cottonseed oil for use in CI engine. Different blends of dual biodiesel are prepared by blending pongamia and cottonseed oil with mineral diesel at different proportions, and the preliminary results are reported in Vejendla *et al*. [11]. As per the knowledge of the authors, this is the first study to utilize dual biodiesel blends of pongamia and cottonseed oil.

II. FUEL PREPARATION AND PROPERTIES

Different blends of the biodiesels are prepared as discussed in the following sections.

A. Production of Biodiesel

The various steps involved in the production of biodiesel are as follows:

1. Transesterification
2. Settling and separation of esters and glycerine
3. Washing of biodiesel
4. Heating

Transesterification is a process that involves oil reacting with short-chained alcohols such as methanol, ethanol, etc. in the presence of a catalyst. In this study, initially, ethanol and Potassium Hydroxide (catalyst) are mixed in a closed vessel. Then, the vegetable oil that is to be made into biodiesel is added to this vessel and is heated to a temperature of 80°C using an electromagnetic heater as shown in Fig. 1.

The reaction is sustained for about 10 hours along with vigorous stirring. The mixture is then cooled and is allowed to settle using a separating funnel for about 12 hours as shown in Fig. 2b. A clear separation of ester and glycerine can be visually seen at this stage (Fig 2). The upper layer consists of methyl ester whereas glycerine is formed in the lower layer. Further, the ester is removed and washed thoroughly with water to obtain a clear ester. This yields biodiesel.

Fig. 1. Electro Magnetic Heater

a) Separation **b) Glycerine**

Fig. 2. Process of Separation and Formation of Glycerine

The primary purpose of washing the ester is to remove any soap formed during the transesterification. Moreover, washing also improves the properties of the fuel by making it glycerine free. Water also helps to neutralize the residual catalyst and also helps to remove the product salts. In this study, three washes have been done for about six hours followed by at least one hour of settling time after each wash, though some studies recommend a longer settling time.

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At the end of each wash, the water is drained by a bottom drain, and the same procedure is repeated. In the last stage, the biofuel would be heated above 100°C to remove remaining ethanol and water particles.

B. Mixing (Preparation) of Dual Blends

Diesel is mixed with pongamia and cottonseed oil based on volume. Firstly, the Dual Biodiesel is filtered from impurities individually. Then, the required amount of fuel and Dual Biodiesel are taken into a measuring jar and mixed thoroughly according to the proportions shown in Table I.

Table I. Blending Percentage of Fuel

Notatio	Fuel Quantity (ml)	Diesel Quantity (ml)	Biodiesel Quantity (ml)	
			CSME	POME
B10	1000	900	70	30
B20	1000	800	140	60
B30	1000	700	210	90

Determination of Properties of Fuel

1) Density Measurement

Density is defined as mass per unit volume. With the help of digital balance, mass is determined for a given unit volume.

2) Calorific Value

The calorific value of a fuel is defined as the thermal energy released per unit quantity of fuel under complete combustion with oxygen in standard condition. Calorific value is determined by *Bomb Calorimeter* for both diesel and biodiesel blends, following the specifications of ASTM D420. Diesel is having a higher calorific value than all the blends. It is inferred that the calorific value decreases as the percentage of dual blends increase with respect to diesel.

3) Viscosity

Kinematic viscosity is determined by *Redwood Viscometer*, following the procedure advised in ASTM D0445. The viscosity of B10 is closer to diesel and increases with the increasing percentage of dual blends.

4) Flash Point and Fire Point

The flash point of a fuel is the lowest temperature at which vapours of the fuel will ignite, under an ignition source. The Fuel fire point is the minimum temperature under which the fuel vapours will burn continuously for at least 5 seconds after ignition. *Pen Sky Test* is used to find the flash and fire point, employing the procedure given in EN ISO 2719.

Table II. Fuel Properties

Fuel Type	Density (kg/m3)	Viscosity (cSt)	Flash Point (°C)	Fire Point (°C)	Calorific Value (kJ/kg)
Diesel	840	4.2	66	72	43000
Pongamia Oil	860	5.14	128	134	37700
Cottonseed oil	880	4.1	224	476	38510
B10	854	4.22	78.92	81.14	40924
B20	859	7.018	384.4	443.2	38847.31
B30	863	8.427	536.4	631.8	36770.97

C. Experiments

Experiments are conducted on the four-stroke, single cylinder, water-cooled VCR diesel engine test rig which shown in Figs. 3 and 4. The tests are conducted with diesel followed by B10, B20 and B30 with varying loads of 0.5, 1, 1.5, 2, and 2.5 kW. The specifications of the diesel engine are listed in Table B of the Appendix.

Fig 3. Experimental Test Engine

The engine was first operated on diesel fuel with no load for few minutes at the rated speed of 1500 rpm. The baseline parameters were obtained at the rated speed by varying load on the engine. Then the fuel is replaced with the cottonseed oil and pongamia dual biodiesel (B10) and test was conducted with the blend of 90% diesel and 10% biodiesel by varying the load on the engine. The same procedure is repeated for B20 and B30 dual biodiesel blends. The brake power is measured by using an electrical dynamometer. The volume of the fuel consumption is measured by using a fuel tank fitted with a burette and a stopwatch. The exhaust gas temperature is measured using an iron-constantan thermocouple.

Fig. 4 Experimental test rig

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Tables III, IV, V, and VI show the various parameters measured/observed during the experiment. From these values, the Brake Thermal Efficiency (BTE) and Brake Specific Fuel Consumption (BSFC) are calculated.

Table III. Experimental Observations for Diesel

Parameter	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
CR	17.1	17.1	17.1	17.1	17.1
Speed (RPM)	1559	1551	1544	1526	1506
Load (kW)	0.5	1	1.5	2	2.5
Voltage (V)	212	203	194	184	167
Current (A)	1.9	3.8	5.5	7	9.5
Time taken for 10 ml of fuel (s)	40.76	34.64	29.7	27062	24.2
Manometer reading (mm)	13	13	13	13	13
Exhaust Gas Temperature (°C)	252	301	330	349	385

Table IV. Experimental Observations for B10

Parameter	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
CR	17:01	17:01	17:01	17:01	17:01
Speed (RPM)	1556	1545	1528	1515	1499
Load (kW)	0.5	1	1.5	2	2.5
Voltage (V)	217	207	200	190	173
Current (A)	1.9	3.9	5.7	7.2	9.9
Time taken for 10 ml of fuel (s)	64.53	52.63	46.53	40.97	33.54
Manometer reading (mm)	5	4	3	3	3
Exhaust Gas Temperature (°C)	258	302	340	370	436

Table V. Experimental Observations for B20

Parameter	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
CR	17:01	17:01	17:01	17:01	17:01
Speed (RPM)	1562	1554	1545	1537	1526
Load (kW)	0.5	1	1.5	2	2.5
Voltage (V)	181	174	165	159	148
Current (A)	1.6	3.2	4.7	6.1	8.4
Time taken for 10 ml of fuel (s)	70.75	60.02	54.22	49.21	42.25
Manometer reading (mm)	5	5	4	3	2
Exhaust Gas Temperature (°C)	218	262	293	321	368

Table VI. Experimental Observations for B30

Parameter	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
CR	17:01	17:01	17:01	17:01	17:01
Speed (RPM)	1548	1543	1536	1526	1516
Load (kW)	0.5	1	1.5	2	2.5
Voltage (V)	179	170	163	156	144
Current (A)	1.6	3.2	4.6	6	8.2
Time taken for 10 ml of fuel (s)	72.69	60.59	54.57	49.43	43
Manometer reading (mm)	2	2	3	1	1
Exhaust Gas Temperature (°C)	227	264	294	320	362

III. NUMERICAL MODELLING

A second-order nonlinear regression model is created to relate the Torque and Speed with BTE and BSFC of the engine when powered by each blend of fuel. BTE and BSFC are initially calculated from the variables observed in the experiment. Following the basic formulae of IC Engine, BTE can be expressed in terms of Mechanical Efficiency (ME) and Indicated Thermal Efficiency (ITE) as given in (1) [12]

$$\mathrm{ME} = \frac{\mathrm{BTE}}{\mathrm{ITE}} \tag{1}$$

Further, BTE can be approximated as a function of Torque (T) and Speed (ω) as given in (2) and (3) respectively

$$\mathrm{BTE} = \mathrm{ME} \cdot \mathrm{ITE} = f(T) \tag{2}$$

$$\mathrm{BTE} = \mathrm{ME} \cdot \mathrm{ITE} = f(\omega) \tag{3}$$

In (2) and (3), $f(T)$ and $f(\omega)$ can be approximated using a second order polynomial equation as given in (4) and (5) respectively

$$f(T) = A_0 + A_1 \cdot T + A_2 \cdot T^2 \tag{4}$$

$$f(\omega) = B_0 + B_1 \cdot \omega + B_2 \cdot \omega^2 \tag{5}$$

Further, BTE can be modelled by combining both the polynomial equations (4) and (5) as

$$\mathrm{BTE} = f(T) \bullet f(\omega)$$

$$\mathrm{BTE} = \left(A_0 + A_1 \cdot T + A_2 \cdot T^2\right) \bullet \left(B_0 + B_1 \cdot \omega + B_2 \cdot \omega^2\right)$$

$$\mathrm{BTE} = \begin{cases} C_0 + C_1\omega + C_2\omega^2 + C_3T + C_4T\omega + \\ C_5T\omega^2 + C_6T^2 + C_7T^2\omega + C_8T^2\omega^2 \end{cases} \tag{6}$$

A similar equation can be derived to model the relationship between Torque, Speed, and BSFC as given below

$$\mathrm{BSFC} = \frac{1}{\mathrm{f}(\omega)} \bullet \frac{1}{\mathrm{f}(\mathrm{T})}$$

$$\frac{1}{\mathrm{BSFC}} = \begin{cases} D_0 + D_1\omega + D_2\omega^2 + D_3T + D_4T\omega \\ D_5T\omega^2 + D_6T^2 + D_7T^2\omega + D_8T^2\omega^2 \end{cases} \tag{7}$$

Multiple linear regression, a statistical correlation technique, is used to estimate the coefficients C_0, … C_8 and D_0, … D_8. They are specific to each fuel blends and engine.

Equations (6) and (7) is used to compute the multiple regression coefficients in MATLAB using the values observed in the experiment.

Different coefficients are computed for each set of fuel viz., Diesel, B10, B20 and B30. After finding the regression coefficients, BTE and BSFC are computed for various values of Torque and Speed by substituting these coefficients in (6) and (7). Contours of BTE and BSFC are generated on the experimental limits of given Torque and Speed. The various plots that have been obtained using these equations are presented in the next section.

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IV. RESULTS AND DISCUSSION

A. Experimental Results

1) Brake Specific fuel consumption (BSFC)

The effect of load on BSFC is shown in Fig. 5. As the load increases, the BSFC decreases for all the dual biodiesel blends. There may be two reasons for this decrease. One would be, with the increase in load, there is an increase in brake power, which would directly reflect in the reduction of BSFC as both are inversely related. Another would be due to the presence of oxygen in the biodiesel and its blends, which enables the combustion, and this will also compensate for the viscosity effects. For the maximum load, the value of BSFC of B10 is 0.401 kg/kWh, B20 is 0.441 kg/kWh, and B30 is 0.458 kg/kWh, whereas mineral diesel fuel is 0.596 kg/kWh.

2) Brake Thermal Efficiency (BTE)

The effect of load on BTE is shown in Fig. 6. BTE is high for all dual biodiesel blends when compared with mineral diesel. Since there are excess oxygen molecules, complete combustion of fuel would be enhanced, and this would correspond to increased efficiency. BTE efficiency is a crucial factor because it is dependent on the calorific value of the fuel. Higher BTE of dual biodiesel blends is due to their lower calorific value.

B. Numerical Modelling Results

From the experimental results, it is clear that B10 has higher BTE and lesser BSFC than mineral diesel, B20 and B30. In order to comprehend the performance of B10 over mineral diesel, regression models for these fuels are developed, since experimental values are limited in terms of the range of torque and speed. The regression model of BTE vs. torque and speed and BSFC vs. torque and speed is developed utilizing the few observations made during the experiment. Moreover, it is not feasible to conduct experiments to find BTE/BSFC for all the values of torque and speed. Hence, the mathematical model comes in handy to predict the BTE/BSFC for a given value of torque and speed.

The experimental values of BTE vs. Speed and Torque and BSFC vs. Speed and Torque has been used to find the coefficients given in (6) and (7) respectively. The multiple linear regressions have been carried out in MATLAB, and the coefficients for different types of fuel are given in Tabled VII and VIII. Figs. 7, 8, 11 and 12 show the data used for fitting the model and the mesh of BTE and BSFC for different fuels. It can be seen that the experimental data lies closely on the mesh for both the fuels. Moreover, the accuracy of the fit is evaluated statistically and is provided in Table VII in terms of R^2 value. Here, the R^2 value for both the models is 1, which indicates a good fit and the generated model can explain all the variability of the engine with sufficient accuracy. The coefficients from Table VII have further been used to plot the model over the same range of speed and torque for which the experiment has been carried out.

Furthermore, the Contour of BTE against Speed and Torque for various blends of fuel namely Diesel and B10 are shown in Figs. 9 and 10. These figures show that the BTE of B10 fuel performs better than diesel. Here the experimental data points we have taken are not sufficient to plot the BTE contours because after reaching the maximum value of BTE, the curve of BTE in BTE vs. Load will decrease, which is missing in the present study, but clearly, the trend for BTE of B10 is higher than that of diesel.

Table VII. Regression coefficients for BTE and BSFC

	Coeff.	Diesel	B10		Coeff.	Diesel	B10
	C_0	0	0		D_0	0	0
	C_1	0	0		D_1	0	0
	C_2	0	0.0004		D_2	-5.50×10-7	2.99×10-5
	C_3	0	0		D_3	0	0
BTE	C_4	0.0714	-0.3335	BSFC	D_4	0.008253	-0.01767
	C_5	-0.0004	0.002		D_5	-4.06×10-5	0.000109
	C_6	0	0		D_6	0	0
	C_7	-0.0001	-0.0282		D_7	1.46×10-5	-0.00194
	C_8	0	0.0002		D_8	-5.92×10-7	1.30×10-5
	R^2	1	1		R^2	1	1

Similarly, the numerical model and data for BSFC for different blends of fuel are given in Figs. 13 and 14. While the corresponding contour of BSFC is shown in figures 16 and 17.BTE and BSFC of the fuel blend ‘B10’ are compared with that of diesel and is plotted in the Figs. 15 and 16 respectively. The pink cells in Fig. 15 shows the negative effect, and the blue cells show a positive effect. It is inferred that mineral diesel shows better results at a lower speed and torque than B10, however, B10 shows better results at higher speed and torque.

The white cells in Fig. 15 indicates the data for which estimated BTE is negative and hence considered as outliers. The pink cells in Fig. 16 indicate the negative effect and the blue cells indicate the positive effect of B10 over mineral diesel with respect to BSFC. BSFC for B10 is lower than mineral diesel at lower speed and torque.

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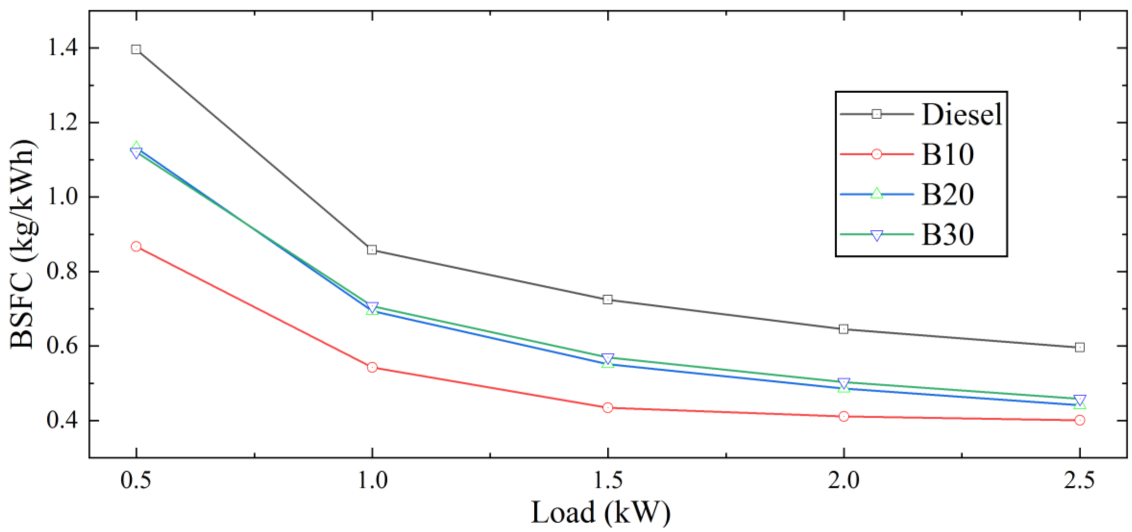

Fig. 5. Variation of Load with Brake Specific Fuel Consumption (BSFC) for different blends of fuel
Brake Thermal Efficiency (%)

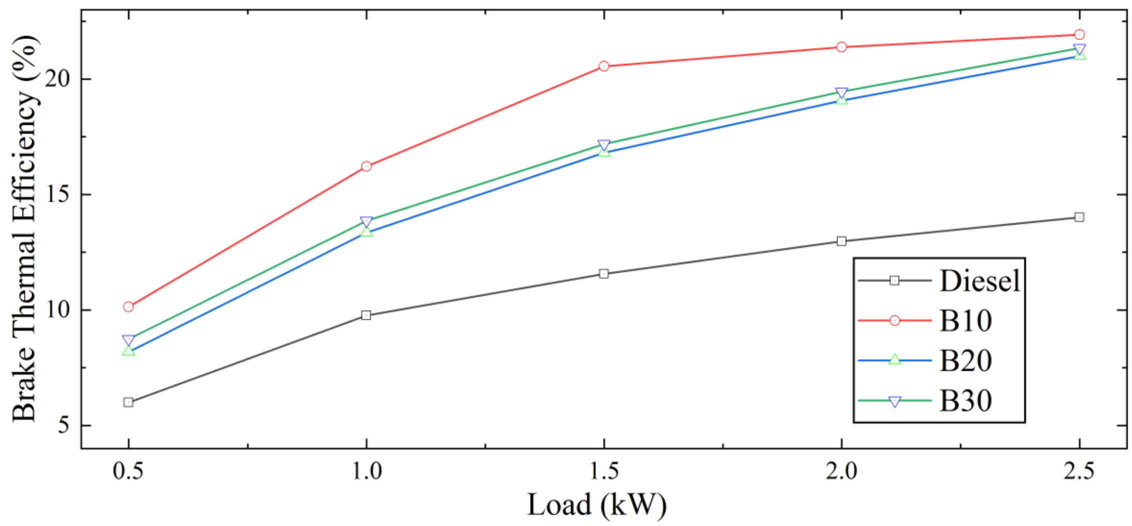

Fig. 6. Effect of load on brake thermal efficiency for different blends of fuel

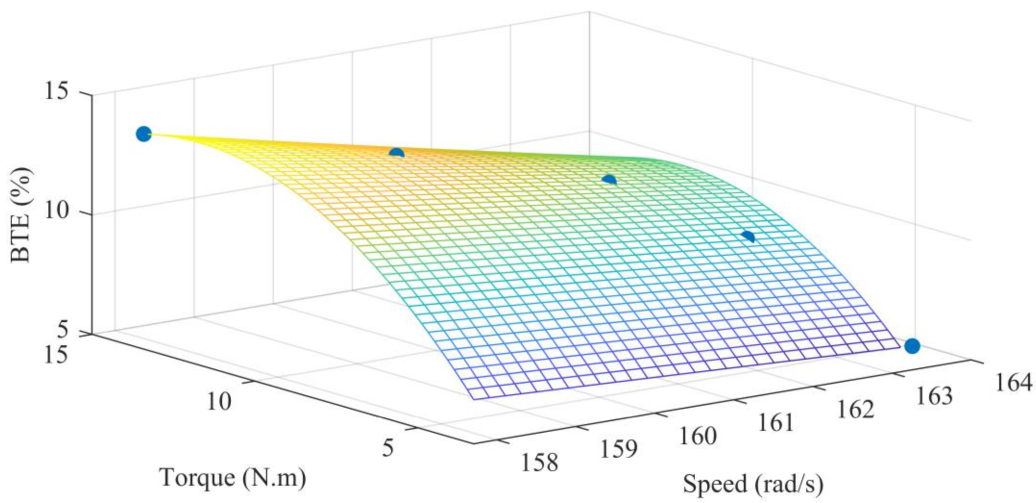

Fig. 7. Experimental Data (blue dots) and regression model (mesh) of Brake Thermal Efficiency (BTE) vs. Torque and Speed of diesel-powered engine

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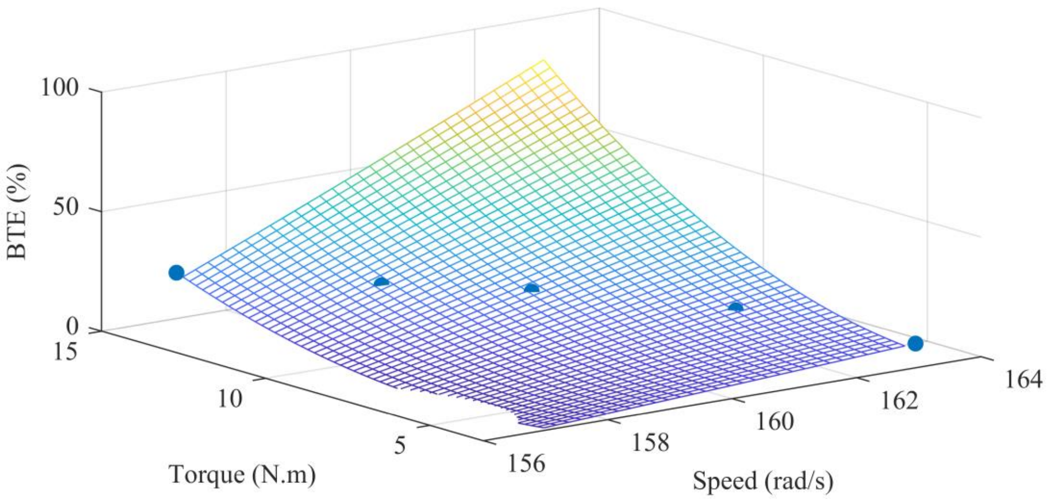

Fig. 8. Experimental Data (blue dots) and regression model (mesh) of Brake Thermal Efficiency (BTE) vs. Torque and Speed of B10 powered engine

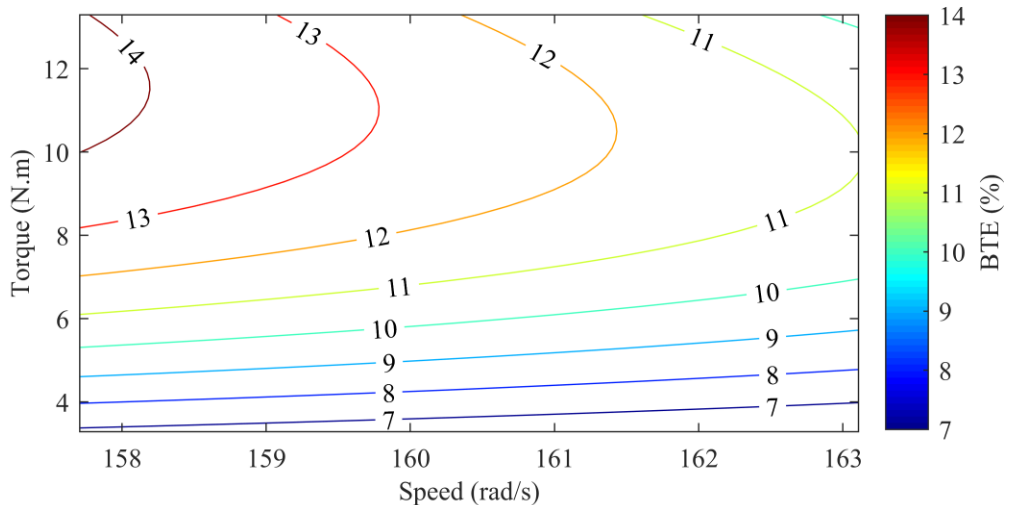

Fig. 9. Contour of BTE obtained from the regression model of the engine fueled by diesel

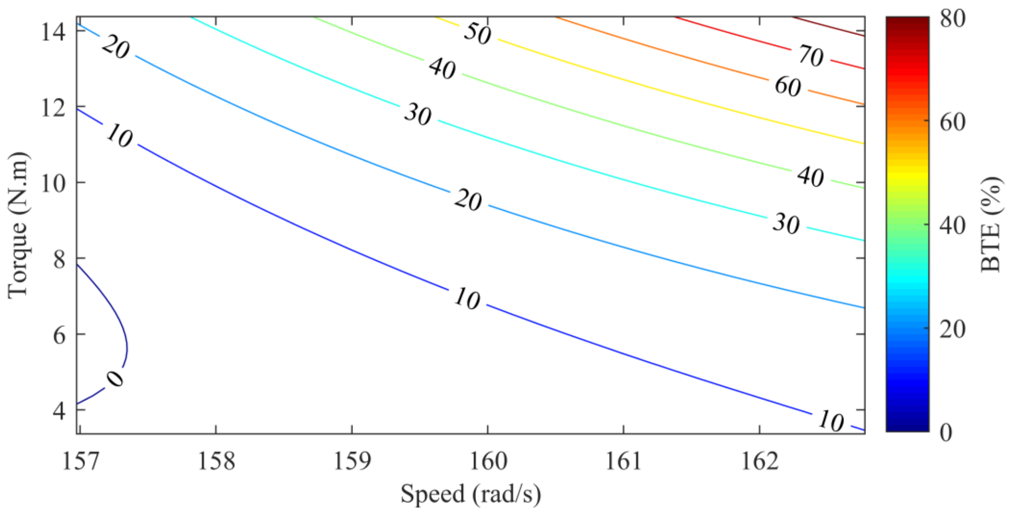

Fig. 10. Contour of BTE obtained from the regression model of the engine fueled by B10

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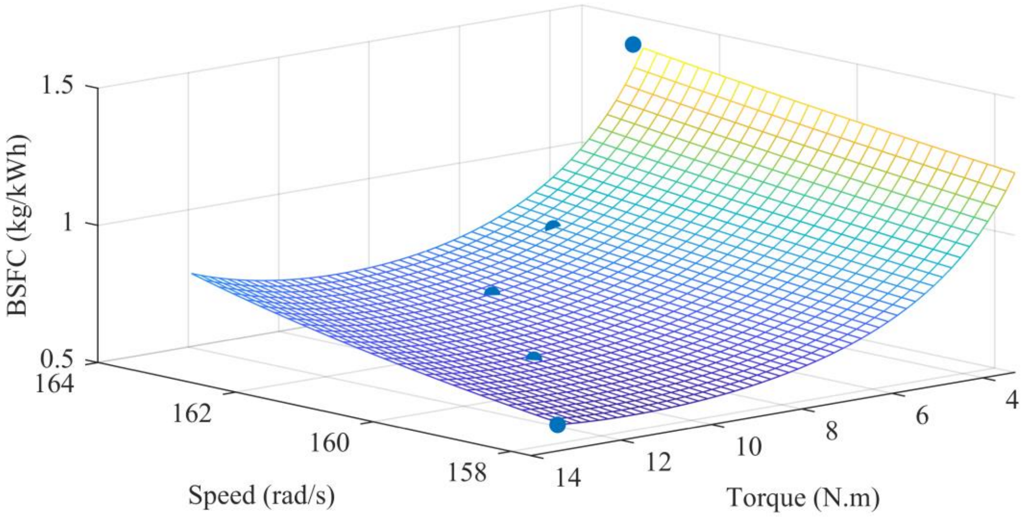

Fig. 11. Experimental Data (blue dots) and regression model (mesh) of Brake Specific Fuel Consumption (BSFC) vs. Torque and Speed of diesel-powered engine

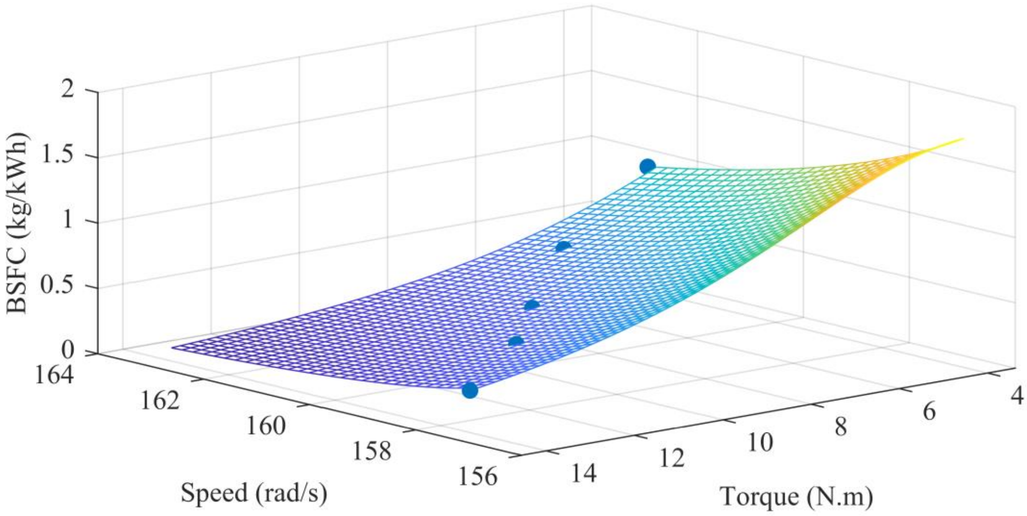

Fig. 12. Experimental Data (blue dots) and regression model (mesh) of Brake Specific Fuel Consumption (BSFC) vs. Torque and Speed of B10 powered engine

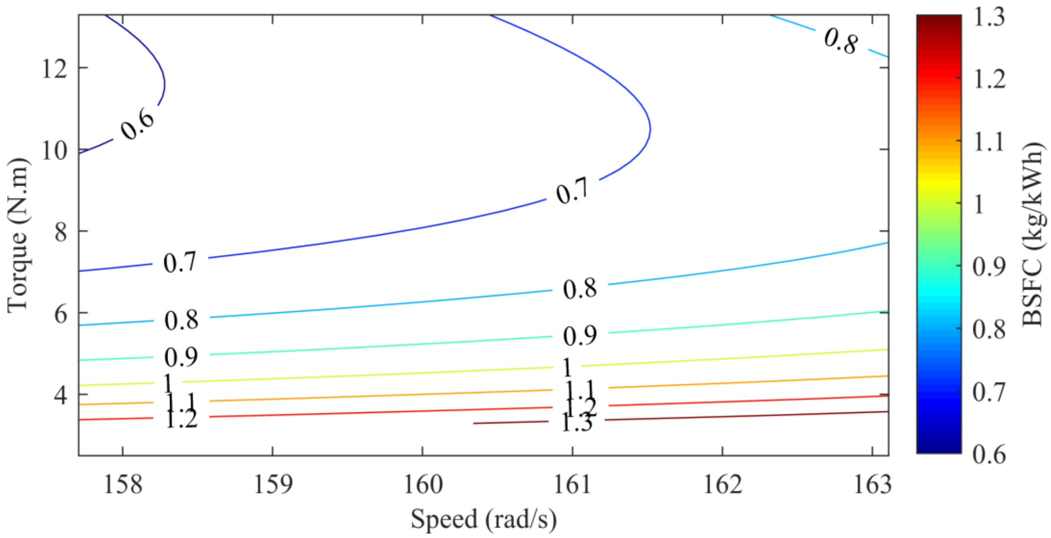

Fig. 13. Contour of BSFC obtained from the regression model of the engine fueled by diesel

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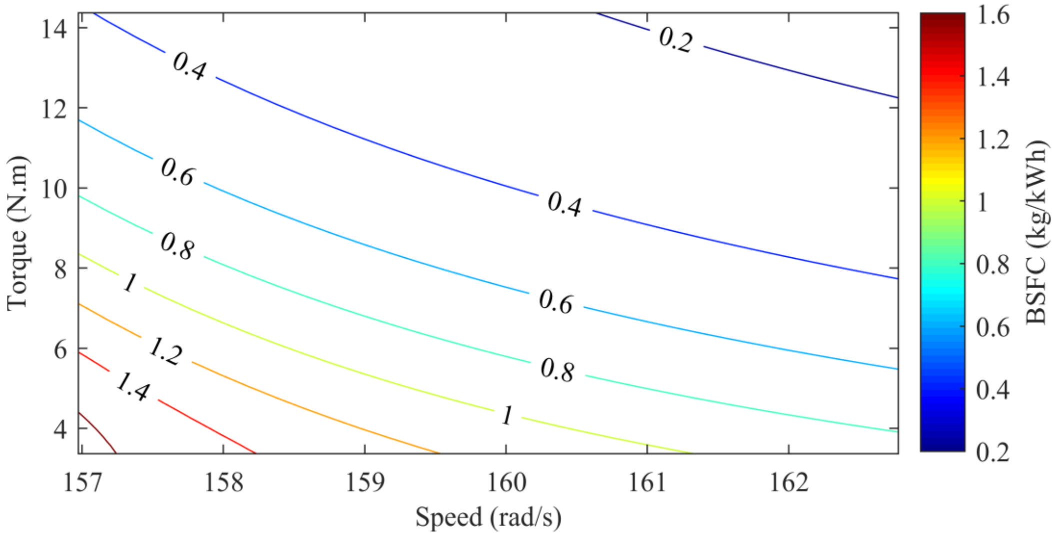

Fig. 14. Contour of BSFC obtained from the regression model of the engine fueled by B10

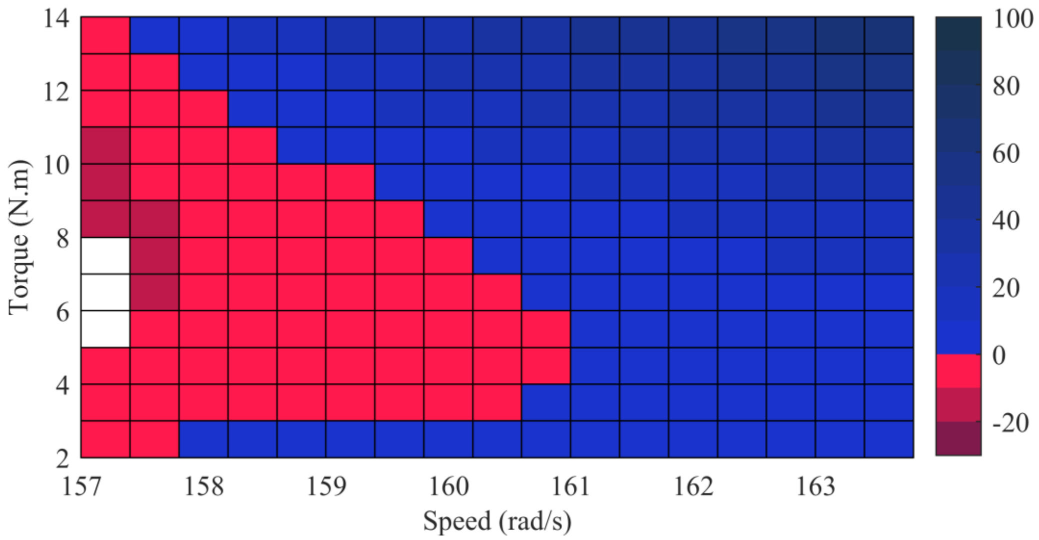

Fig. 15. Difference in the BTE of engine powered by B10 to that of engine powered by diesel.

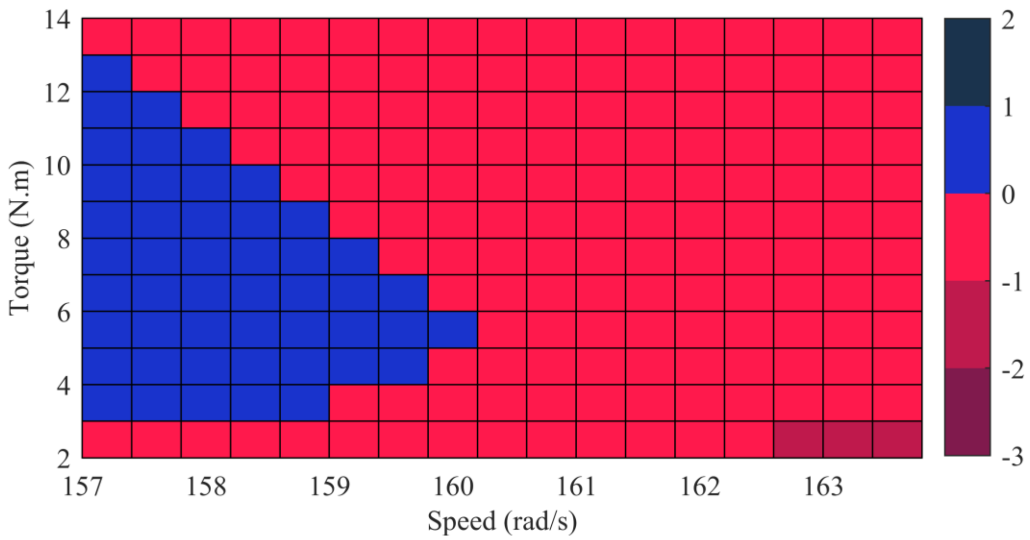

Fig. 16. Difference in the BSFC of engine powered by B10 to that of engine powered by diesel.

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V. CONCLUSION

In this study, experimental and numerical modelling of dual biodiesel blends of pongamia and cottonseed oil has been described. The dual biodiesel blends of cottonseed and pongamia oil are successfully tested on VCR diesel engine. This is the first study to attempt these dual fuels, and the results clearly show that dual biodiesels of cottonseed and pongamia oil can be used as an alternative to diesel and single biodiesels. The highlights of this study are enumerated below.

1. The mineral diesel and the dual biodiesels of cottonseed and pongamia oil are characterized, and their various chemical, physical and thermal properties were measured.
2. From the experiment, the Brake Thermal Efficiency (BTE) of B10 is found to be higher than diesel. Whereas BTE of B20 and B30 were close to that of diesel. The Brake Specific Fuel Consumption (BSFC) of B10 is lower than mineral diesel, and the BSFC for B20 and B30 are almost the same. This can be chiefly attributed to the presence of oxygen in the biodiesel blends that enables complete combustion. Among the three blends, i.e., B10, B20 and B30, B10 is found to be the best.
3. A regression model of BTE and BSFC is developed for VCR engine for B10 and mineral Diesel using the parameters observed in the experiment. The developed mathematical model closely correlates with experimental observations. The contour of BTE and BSFC show that higher values of BTE and lower values of BSFC is possible for various combinations of speed and torque. Using the regression model, it is found that B10 indicates better performance in terms of BTE and BSFC than mineral diesel.

APPENDIX

Table A. Nomenclature

So_x	Sulfur Oxides
CO_2	Carbon dioxide
NO_x	Oxides of Nitrogen
B10	90% diesel, 3% pongamia oil and 7% cottonseed oil by volume
B20	80% diesel, 6% pongamia oil and 14% cottonseed oil by volume
B30	70% diesel, 9% pongamia oil and 21% cottonseed oil by volume
CO	Carbon Monoxide
HC	Hydrocarbon
CSME	Cottonseed Oil Methyl Ester
POME	Pongamia Oil Methyl Ester
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
BP	Brake Power

Table B. Engine Specifications

Engine	Four Stroke Single Cylinder
Make	Kirloskar
BHP	5 HP
Speed	1500 rpm
Fuel	DIESEL
Bore	80 mm
Stroke Length	110 mm
Starting	Cranking
Working Cycle	Four Stroke
Method of Cooling	Water Cooled
Method of Ignition	Compression Ignition

A. MATLAB code for Regression Analysis of BTE

```
clear
clc
close all
FontSize = 10;

speed_rpm = [1559; 1551; 1544; 1526; 1506];
    %Speed in rpm
BP = [0.537; 1.0285; 1.4226; 1.717; 2.115];
    %Brake Power in kW
Load = [0.5; 1; 1.5; 2; 2.5]; %Load in kg
T = (BP./speed_rpm)*(60*1000/(2*pi));
    %Torque in N.m
speed_rs = speed_rpm.*2*pi/60; %Speed in
    rad/sec

BTE_val = [5.99; 9.767; 11.56; 12.98;
    14.009];

X = [ones(5,1), speed_rs, speed_rs.^2, T,
    T.*speed_rs, T.*speed_rs.^2, T.^2,
    T.^2.*speed_rs, T.^2.*speed_rs.^2];

Coeff = regress(BTE_val,X);

%% BTE surface plot
f1 = figure('Units', 'centimeter',
    'Position', [0 0 15 7],
    'PaperPositionMode', 'auto');
scatter3(speed_rs, T, BTE_val, 'filled')
hold on
speed_rs_fit =
    min(speed_rs):0.2:max(speed_rs);
T_fit = min(T):0.2:max(T);
[speed_rs_ FIT, T_FIT] =
    meshgrid(speed_rs_fit, T_fit);
YFIT = Coeff(1) + Coeff(2)*speed_rs_FIT +
    Coeff(3)*speed_rs_FIT.^2 +
    Coeff(4)*T_FIT +
    Coeff(5)*T_FIT.*speed_rs_FIT +
    Coeff(6)*T_FIT.*speed_rs_FIT.^2 +
    Coeff(7)*T_FIT.^2 +
```


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```
    Coeff(8)*T_FIT.^2.*speed_rs_FIT +
    Coeff(9)*T_FIT.^2.*speed_rs_FIT.^2;
mesh(speed_rs_FIT, T_FIT, YFIT)
xlabel('Speed (rad/s)', 'FontName',
    'Times', 'FontSize', FontSize)
ylabel('Torque (N.m)', 'FontName',
    'Times', 'FontSize', FontSize)
zlabel('BTE (%)', 'FontName', 'Times',
    'FontSize', FontSize)
set(findall(gcf, '-property',
    'FontSize'), 'FontSize', FontSize)
set(findall(gcf, '-property',
    'FontName'), 'FontName', 'Times')
print(gcf, 'BTE_B0_fit', '-dpng','-r600')
%% Save as PNG file

%% BTE contour plot
f2 = figure('Units', 'centimeter',
    'Position', [0 0 15 7],
    'PaperPositionMode', 'auto');
[C, h] = contour(speed_rs_FIT, T_FIT, YFIT,
    'ShowText', 'on');
colormap jet
hcb = colorbar;
xlabel('Speed (rad/s)', 'FontName',
    'Times', 'FontSize', FontSize)
ylabel('Torque (N.m)', 'FontName',
    'Times', 'FontSize', FontSize)
zlabel('BTE (%)', 'FontName', 'Times',
    'FontSize', FontSize)
clabel(C, h, 'FontSize', FontSize,
    'Color', 'black', 'FontName', 'Times')
ylabel(hcb, 'BTE (%)', 'FontName',
    'Times', 'FontSize', FontSize)
set(findall(gcf, '-property','FontSize'),
    'FontSize', FontSize)
set(findall(gcf,'-property','FontName'),
    'FontName', 'Times')
print(gcf,'BTE_B0_cont','-dpng','-r600')
%% Save as PNG file
```

B. MATLAB code for Regression Analysis of BSFC

```
clear
clc
close all
FontSize = 10;

speed_rpm = [1559; 1551; 1544; 1526; 1506];
    %Speed in rpm
BP = [0.537; 1.0285; 1.4226; 1.717; 2.115];
    %Brake Power in kW
Load = [0.5; 1; 1.5; 2; 2.5]; %Load in kg
T = (BP./speed_rpm)*(60*1000/(2*pi));
    %Torque in N.m
speed_rs = speed_rpm.*2*pi/60; %Speed in
    rad/sec

BSFC_val = [1.396; 0.857; 0.724; 0.6447;
    0.596];

X = [ones(5, 1), speed_rs, speed_rs.^2, T,
    T.*speed_rs, T.*speed_rs.^2, T.^2,
    T.^2.*speed_rs, T.^2.*speed_rs.^2];

Coeff = regress(1./BSFC_val,X);

%% BSFC surface plot
f1 = figure('Units', 'centimeters',
    'Position',[0 0 15 7],
    'PaperPositionMode', 'auto');
scatter3(speed_rs, T, BSFC_val, 'filled')
hold on
speed_rs_fit =
    min(speed_rs):0.2:max(speed_rs);
T_fit = min(T):0.2:max(T);
[speed_rs_FIT, T_FIT] =
    meshgrid(speed_rs_fit, T_fit);
YFIT = Coeff(1) + Coeff(2)*speed_rs_FIT +
    Coeff(3)*speed_rs_FIT.^2 +
    Coeff(4)*T_FIT +
    Coeff(5)*T_FIT.*speed_rs_FIT +
    Coeff(6)*T_FIT.*speed_rs_FIT.^2 +
    Coeff(7)*T_FIT.^2 +
    Coeff(8)*T_FIT.^2.*speed_rs_FIT +
    Coeff(9)*T_FIT.^2.*speed_rs_FIT.^2;
mesh(speed_rs_FIT,T_FIT,1./YFIT)
xlabel('Speed (rad/s)', 'FontName',
    'Times', 'FontSize', FontSize)
ylabel('Torque (N.m)', 'FontName',
    'Times', 'FontSize', FontSize)
zlabel('BSFC (kg/kWh)', 'FontName',
    'Times', 'FontSize', FontSize)
set(findall(gcf,'-property','FontSize'),
    'FontSize', FontSize)
set(findall(gcf,'-property','FontName'),
    'FontName', 'Times')
print(gcf,'BSFC_B0_fit','-dpng','-r600')


%% BSFC contour plot
f2 = figure('Units', 'centimeters',
    'Position', [0 0 15 7],
     'PaperPositionMode', 'auto');
[C,h] = contour(speed_rs_FIT, T_FIT,
    1./YFIT, 'ShowText', 'on');
colormap jet
hcb = colorbar;
xlabel('Speed (rad/s)', 'FontName',
    'Times','FontSize', FontSize)
ylabel('Torque (N.m)', 'FontName',
    'Times','FontSize', FontSize)
zlabel('BSFC (kg/kWh)', 'FontName',
    'Times','FontSize', FontSize)
clabel(C,h,'FontSize', FontSize,'Color',
    'black', 'FontName', 'Times')
ylabel(hcb, 'BSFC (kg/kWh)', 'FontName',
    'Times', 'FontSize', FontSize)
set(findall(gcf,'-property','FontSize'),
    'FontSize', FontSize)
set(findall(gcf,'-property','FontName'),
    'FontName','Times')
ylim([2.5 13.2893])
print(gcf,'BSFC_B0_cont', '-dpng',
    '-r600')
```


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