

Application of Computational Tools for Performance Prediction of Gasoline Engine Fuelled with Ethanol Gasoline Fuel Fractions

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Abstract:

With faster depletion of natural sources of petroleum fuels, it becomes essential to use alternative fuels. Ethanol is growingly becoming best choice as fuel fraction to blend with gasoline. These fuel fractions are planning to be used with higher percentages of ethanol. It is highly required to find the best possible fuel fractions and performance of the engine under different operating conditions. The present study proposes applications of Minitab and XLSTAT for establishing the relationship of dependent parameters with each independent parameter. Minitab is used for multiple regression and provides mathematical equations for each dependent variable in terms of operating independent variables. Minitab is also used for plotting the contour graphs, which shows the regions of best and poor levels of each dependent parameter on graph through contours and shaded areas. These applications of Minitab are used for performance prediction and finding optimum conditions of engine. XLSTAT is add-on tool to be used in MS-Excel. It provides graphical tools for finding the errors in the model developed. It also gives the dominance of each operating parameter with engine output parameters. Both tools can be effectively used for developing customised mathematical relations. Semi-empirical mathematical relations are simple to form and accurate to predict the engine performance.

Keywords:

Minitab 17, XLSTAT, Ethanol-Gasoline Fuel Fractions, Engine Performance, Computational Tools

1 Introduction:

Engines are running on fossil fuels across the globe and the demand for fuel is increasing every day. At the same time, the need for alternative fuels is increasing at rapid rate, due to hazardous environmental effects and faster depletion of fossil fuels. Researchers are focussing the attention to find the best possible alternatives to the conventional fuels.

Ethanol is rapidly gaining the importance as best fuel addition in conventional gasoline. The fuel fractions of ethanol and gasoline up to 10% ethanol blends are already used in India. Efforts are going to find the next best possible fuel fractions with least engine modifications and best emission performance of the engine. In this direction of research, it is important to find optimum engine performance taking in to consideration, various engine performance parameters and exhaust emissions. It is also important to predict the performance of the engine at different operating conditions. It is vital to explore various models to predict the engine performance and emissions, before the engine trials are conducted. Various researchers have taken efforts in this direction to develop mathematical models. The researchers have used Artificial Neural Network (ANN), mathematical models or empirical equations for engine performance prediction. These prediction models decrease the time of study and it becomes possible to predict the engine performance characteristics, before conducting actual tests on the engine.

Mathematical models can be developed on fluid dynamics or thermodynamics basis. Laws and fundamentals of thermodynamics are used for developing thermodynamic models [1]. Thermodynamic models are based on chemical composition of the reactants in the engine cylinder, chemical reactions, exhaust gases produced, temperatures and unburned fuel and gases [2]. Ismet Sezer and Atilla Bilgin developed two-zone quasi-dimensional model. They did not involve fluid motion calculations and simulated the turbulent flame propagation process. Model is validated with experimental data [3]. Similar models are developed by J. M. Mantilla et.al. and their models are validated with engine experimental data. The model has given the accuracy in 5 % [4]. A quasi-dimensional model developed has the ability to compute engine cycles using ethanol-gasoline fuel fractions and suggested to use the same for further parametric studies [5,13]. M Al-Hasan investigated the effect of ethanol-gasoline fuel fractions using his mathematical models and observed the results for various engine performance parameters and exhaust emissions. He observed that 20% ethanol produced the best results for all parameters [6]. Murugan Sivalingam et.al. developed engine models for blending ethanol with diesel to predict the cylinder pressure, ignition delay, nitric oxides (NO_x) and smoke emissions [7]. Multivariable non-linear and multivariable exponential models are proposed by M. K. Oduola and A. I. Iyaomolere. This model was used to predict three important properties, research octane number, specific gravity and Reid vapour pressure [8]. Ismet Sezer et.al. also used two-zone quasi-dimensional model. This model is based on compression ratio, combustion and expansion in engine cylinder. Simulation of combustion process is done by flame propagation process. Exergy analysis approach is also used for investigation of the performance of the engine [9-11]. Along with prediction of engine performance parameters, it is also required to predict and analyse exhaust emissions from the engine, when we run on different fuel fractions. The study shows that, there is no fixed relationship of emissions with engine operating parameters and case based close relations may need to be developed [12]. Mathematical models are also developed for fuel fractions of ethanol and methanol with pure gasoline. Popularly used quasi-dimensional model is used for the same purpose [13]. Efforts have been taken by B.M. Masum et.al. to predict emissions of NO_x and CO₂ in their research work [14]. Simulink is used to find the performance of engine by Ashish J.Chaudhari et.al. in their research work. They used a zero-dimensional single-zone model for any fuel based on Wiebe heat release function [15]. Mathematical model is are developed for bi-fuel engine based on two-zone combustion model. It has the capability to predict various engine parameters like cylinder pressure and temperature, brake power, various efficiencies, brake torque, specific

fuel consumption, NO_x etc [16]. Mass transfer analysis and combustion analysis are presented by Shintre Parag et.al. The model developed and the research work by the authors presented results of emissions prediction [17].

Models are developed for predicting engine torque and specific fuel consumption based on ignition timing, compression ratio and relative air-fuel ratio. Artificial Neural Network (ANN) with Levenberg-Marquardt (LM) algorithm was used giving fair accuracy validated with engine test data [18-21]. For finding the optimum performance and nature of dependant parameters with reference to independent parameters, Response Surface Methodology [22,23]. Relationship of dependent parameters can be found in various mathematical forms. A Gaussian relationship is proposed by S. Phuangwongtrakul et.al. in their research work [24]. Engine performance simulations software like GT-Power simulation software [25] and AVL Boost [26] are used by some of the researchers to avoid physical testing of the engines and fairly predict the performance.

Researchers have used different approaches to develop the prediction models. Most of the models are mathematical models. These models provide complex equations and may not be possible to manually solve all the equations in the model proposed. It is also difficult to exactly find the predominant factor affecting the dependent variables. Graphical or visual tools are required to be used for better understanding of the relationship of the parameters to find the optimum operating condition of the engine. Present study proposes use of some of the computational tools for finding the exact relationship of dependent and independent variables. This study also provides the solution to find the correctness and closeness of the prediction models.

2 Experimentation:

The experimental setup consists of a Variable Compression Ratio (VCR) engine having a facility of changing the compression ratio in the range of 7 to 10. It is also a multi-fuel engine which can run on various fuels. This engine setup is a computerized setup with a facility to gather all the information from the engine, compile and analyze the data to plot the graphs of the result. Lab view based engine performance analysis software package “Enginesoft” is provided for online performance evaluation. Computer can be connected to the control panel using USB port for collection of data from engine in Enginesoft and the software also plots various engine performance curves. The setup enables study of VCR engine performance for brake power, indicated power, frictional power, mean effective pressures, brake thermal efficiency, indicated thermal efficiency, mechanical efficiency, volumetric efficiency, specific fuel consumption, A/F ratio, heat balance and combustion analysis.

The operation mode of the engine can be changed from one fuel to another with some necessary changes in engine setup. The compression ratio can be varied in engine running condition and without altering the combustion chamber geometry by specially designed tilting cylinder block arrangement.

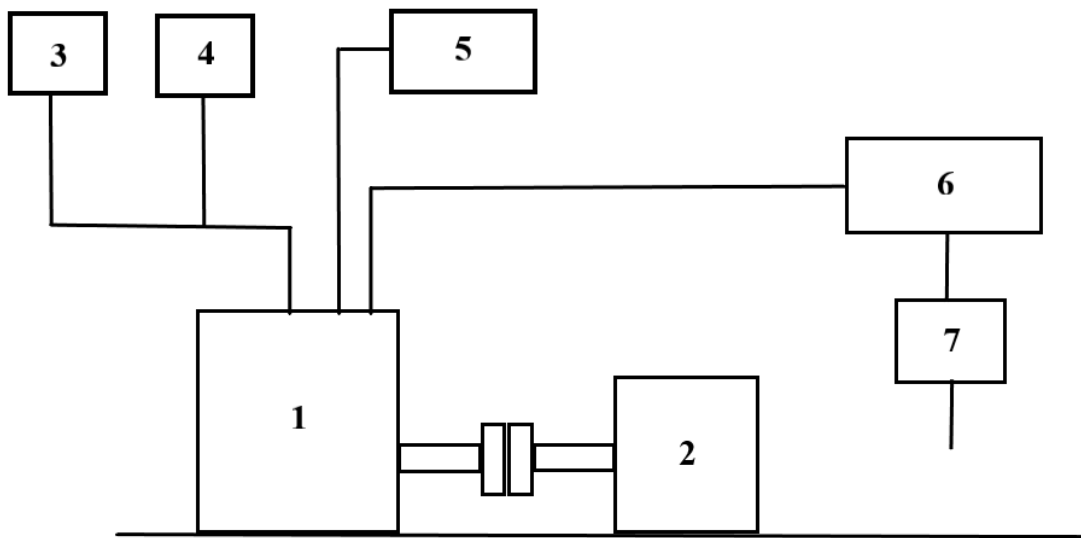


Fig. 1. Engine Experimental Setup

As shown in Fig.1, Engine 1 is connected to Eddy Current Dynamometer 2 through the coupling. This dynamometer is used for loading the engine. Two fuel tanks 3 and 4 are provided in the setup. These fuel tanks supply two different fuels to the engine. Tank 3 supplies pure gasoline, while tank 4 supplies blends of ethanol and gasoline. Panel 5 has controllers for engine loads, throttle, water flow control etc. This panel also has inbuilt sensors for measuring air flow and fuel flow. It displays various engine parameters like engine load, water flow rate, various temperatures, engine speed, air and fuel flow rates etc. Exhaust gas calorimeter 6 is used for finding the heat losses to exhaust gases. Water circulated in this calorimeter is used for absorbing the heat from the exhaust gases. After this calorimeter, exhaust gases are tapped in exhaust gas analyser 7 for measurement of various exhaust gas contents.

Engine is run for 15 to 20 minutes for allowing the time to bring the engine at steady state. All the readings are taken after steady state. Fuel blends are prepared using various fuel fractions of ethanol and gasoline. 10 % ethanol mixed with 90% gasoline by volume is treated as E10. Similarly, fuel fractions are prepared for E20, E30 and E40. Readings are taken at Wide Open Throttle (WOT) condition. Engine is loaded by applying load through eddy current dynamometer. The speed of the engine at the beginning is matched with its highest rated speed and gradually the speed of the engine is reduced by increasing the load on the engine. Reading are taken from 1700rpm to 1300 rpm in the interval of 100rpm. For each single fuel fraction, compression ratio of the engine is also changed from 7 to 10 at the interval of 1. Performance of the engine is observed for each fuel fraction with change in compression ratio and speed of the engine. The data collected after tests is used for analysis of performance of the engine.

3. Use of computational tools:

For predicting the performance of the engine, various mathematical tools are present. However, considering the operating conditions of the engine, in this research work, and fuel fractions used, it is difficult to arrive at complete prediction model using mathematical tools.

Minitab 17 software and XLSTAT plugin are used in the present research work for following applications:

3.1 Use of Minitab 17 for regression analysis:

The engine is operated at different operating independent parameters viz engine speed (N, rpm), fuel fraction and Compression Ratio (CR). Calorific Value (Cv) of the fuel fractions changes due to difference in Cv of Ethanol and Gasoline. Performance of the engine is observed through different dependent variables viz Brake Power (BP), Indicated Power (IP), Brake Specific Fuel Consumption (BSFC), Brake Mean Effective Pressure (BMEP), Indicated Mean Effective Pressure (IMEP) and various efficiencies of the engine. It is important to establish the relationship of dependent parameters with the independent parameters. Regression tool is used in Minitab 17 to establish this relationship. Regression establishes an equation, which can describe the relation among one or more predictor with the response variable.

Following relations are found out after completion of the regression analysis in Minitab 17.

$$BP = 0.000031Cv + 0.000609N + 0.1042CR \quad (1)$$

$$BMEP = 0.000105Cv - 0.001250N + .01479CR \quad (2)$$

$$IMEP = 0.000109Cv - 0.000212N + 0.0778CR \quad (3)$$

$$SFC = 0.000002Cv + 0.000211N - 0.00352CR \quad (4)$$

The accuracy of prediction of these equations can be observed by observing R-Square values.

Table 1: Values of R Square generated in Regression Analysis

Parameter	R Square, %	R Square Adj, %	R Square Pred, %
BP	99.79	99.78	99.78
BMEP	99.89	99.88	99.88
IMEP	99.92	99.91	99.91
BSFC	98.9	98.87	98.84

It is observed in Table 1 that, R Square values of BP, BMEP, IMEP are above 99 % while that for BSFC is above 98%. This is the first parameter to observe the accuracy of the prediction equations. However, the capabilities of the Eq. 1 to Eq. 4 are also observed through R Square Adjusted. It is the percentage of variation in the response, explained by the model, adjusted for the number of predictors in the model relative to number of observations.

It is used for comparing the descriptive power of the regression model including diverse numbers of predictors. Adjusted R-Square compensates for the addition of variables and only increases if the new term enhances the model above what would be obtained by probability. This value is also found more than 99% for BP, BMEP, IMEP and more than 98 % for BSFC.

Prediction ability of the model equations is decided by Predicted R-Square values. In Table 1, it is observed that Predicted R-Square values are more than 99 % for BP, BMEP, IMEP and more than 98 % for BSFC. It shows a very high value for each equation and best ability of each regression equation for prediction ability. These values of Predicted R-Square are also more helpful than adjusted R-Square for comparing models, as it is calculated with observations that may not be included in the model calculations.

Using the model Eq. 1 to Eq.4, the predicted values of the dependant variables BP, BMEP, IMEP and BSFC are calculated. These predicted values are then compared with the actual values of these parameters observed during the experimentation. Total 100 experiments are performed. To find the closeness of the predicted values with the actual values, errors are calculated.

$$E = \frac{\Delta P}{Pa} \times 100$$

Where,

$E = \text{Percentage Error}$

$\Delta P = \text{Actual vlaue of paramter} - \text{predicted value of parameter}$

$Pa = \text{Actual value of paramter}$

The percentage errors for each of the dependant parameters are plotted on the graphs.

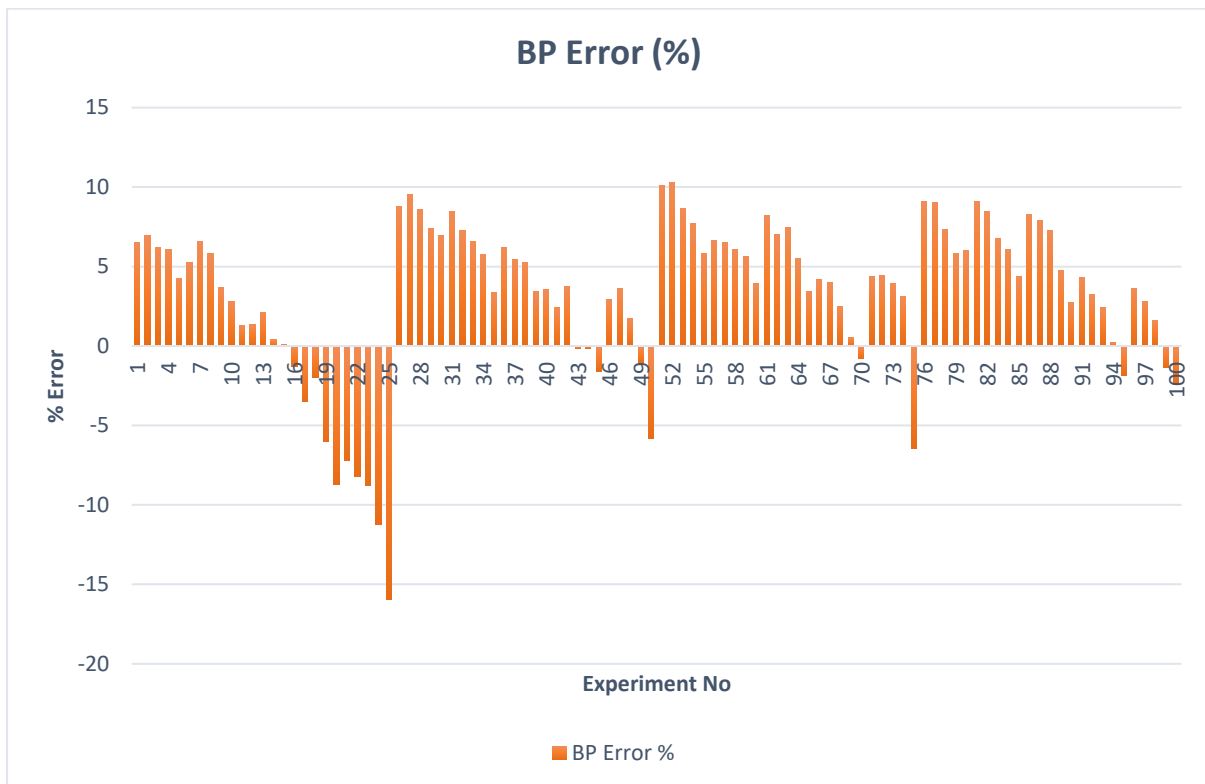


Fig 2 Percentage Error of predicted BP compared with actual BP

It is noted in Fig 2 that percentage errors of BP are on both positive and negative sides. These errors lie between +10% and -16%. The largest deviation is on the negative side for experiments numbers 24 and 25. Except these experiments 24 and 25, the errors are spread within $\pm 10\%$. This gives good prediction ability of the model equation for BP.

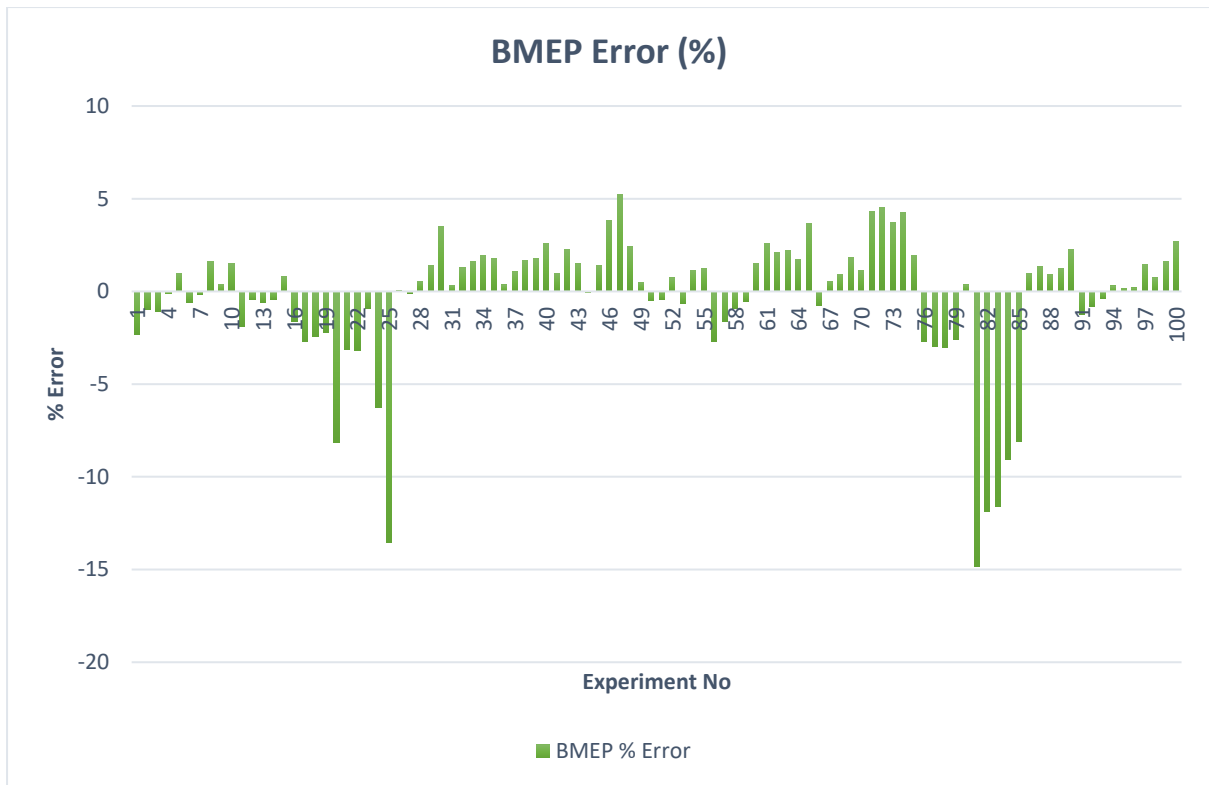


Fig 3 Percentage Error of predicted BMEP compared with actual BMEP

In Fig 3, it is noted that, the errors are spread in both directions and within 5% in positive side. On the negative side, the errors are spread within 5%, except 9 experiments. Errors are observed up to 15% for experiments 19,24,25 and also for 81 to 85. The errors may be due to the prediction ability of the model equation or due to the errors in experimentation. However, the equation generated by regression can be used for predicting BMEP with fair accuracy of prediction.

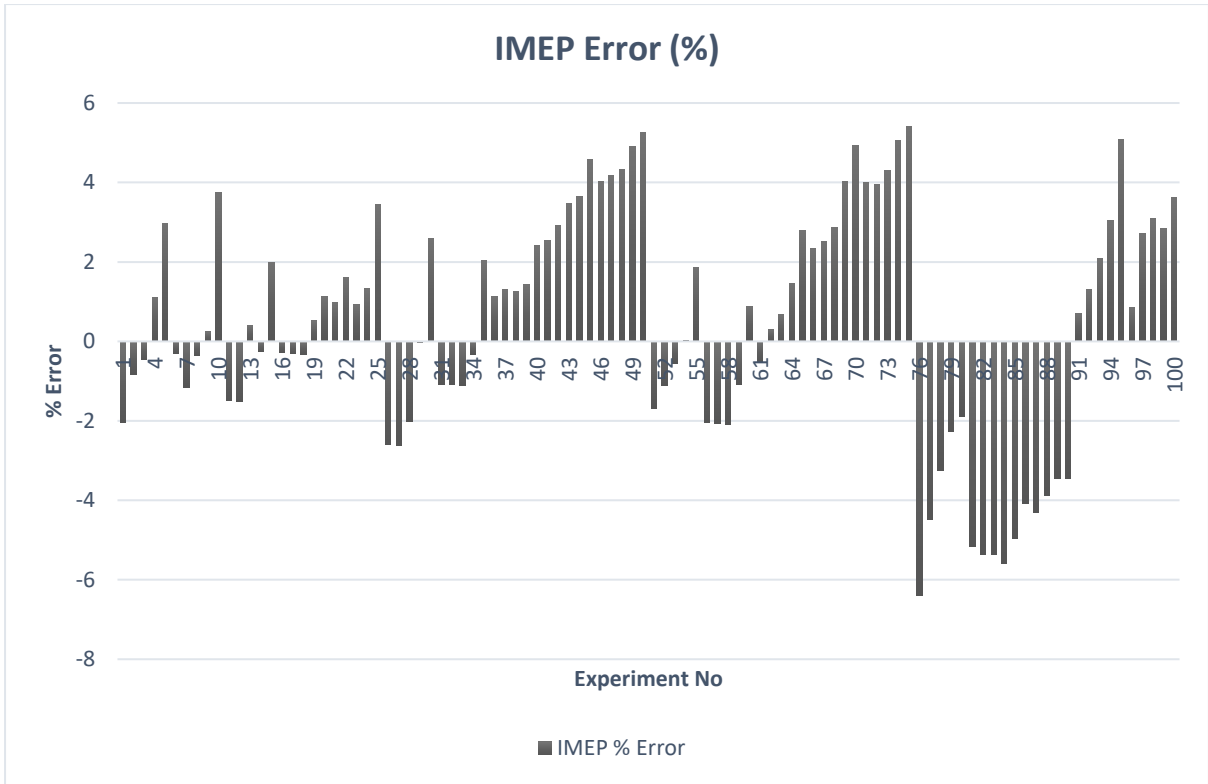


Fig 4 Percentage Error of predicted IMEP compared with actual IMEP

Model equation of regression analysis for IMEP gives the best closeness of predicted values as compared with actual values of IMEP as shown in Fig 4. It is observed that the spread of the errors is within $\pm 7\%$. This is a very good accuracy for prediction.

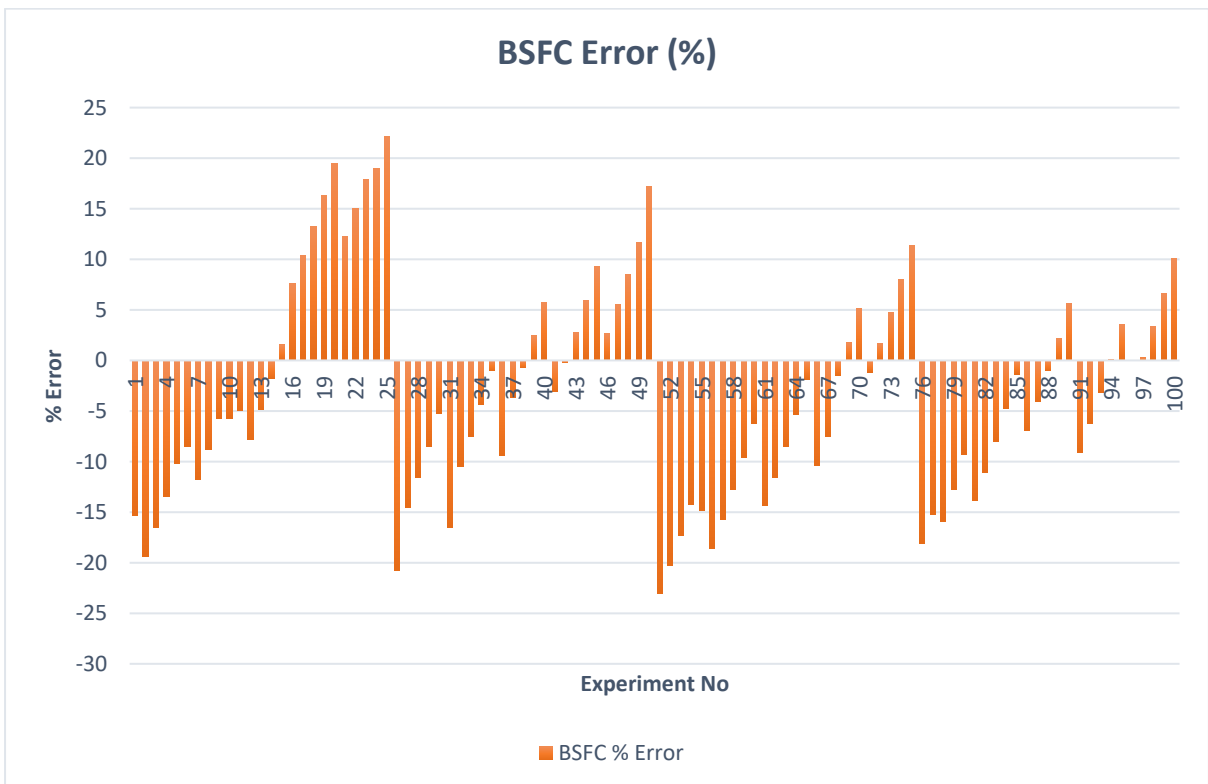


Fig 5 Percentage Error of predicted BSFC compared with actual BSFC

Prediction of BSFC by the model equation is not vary accurate as compared with other dependant parameters. The spread of error is within $\pm 20\%$ for most of the experiments. It is more than this limit for experiments 25, 26 and 50. The equation generated is a linear equation and the larger percentage errors may be due to the assumption of fitting linear equation.

3.2 Use of Minitab 17 for Contour Plots:

Contour plots are used to find the response variable relationship with two predictor variables. It also gives two-dimensional view, wherein, points with same response are connected in such a way to form contour lines and same responses. These plots are very helpful to investigate the desirable response parameters with reference to independent operating variables. Contour plots have predictors on X & Y axes. It also has lines connected with same response values and coloured bands, representing ranges of same response variables.

In the present study, three independent variables are used for prediction of engine performance and conducting engine tests accordingly. These parameters are Cv, Speed and CR. Before plotting these plots, it is observed that the best operating conditions of the engine are observed at CR10. It is also required to use only two independent variables on X and Y axis respectively. Considering the constraints and the best performance condition of engine at CR10, the contour plots are plotted here, as a sample study, to study the use of contour plots.

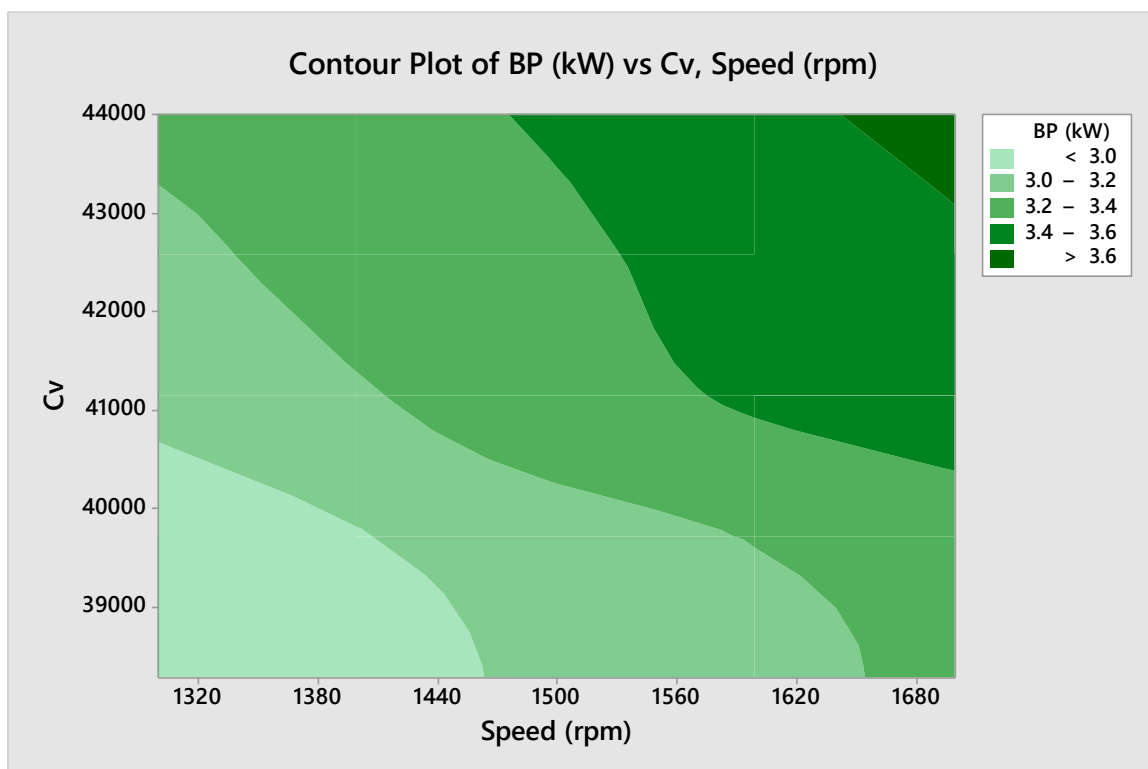


Fig 6 Contour plot of BP

Contour plot of BP, as shown in Fig 6, gives the highest operating condition of the engine with engine speed 1650 to 1700 rpm and Cv more than 43000. This also gives the indication that for the highest BP, the engine should be operated at this operating condition. The next best engine operating condition may be speed 1470 to 1700 rpm and Cv more than 40500 kJ/kWhr.

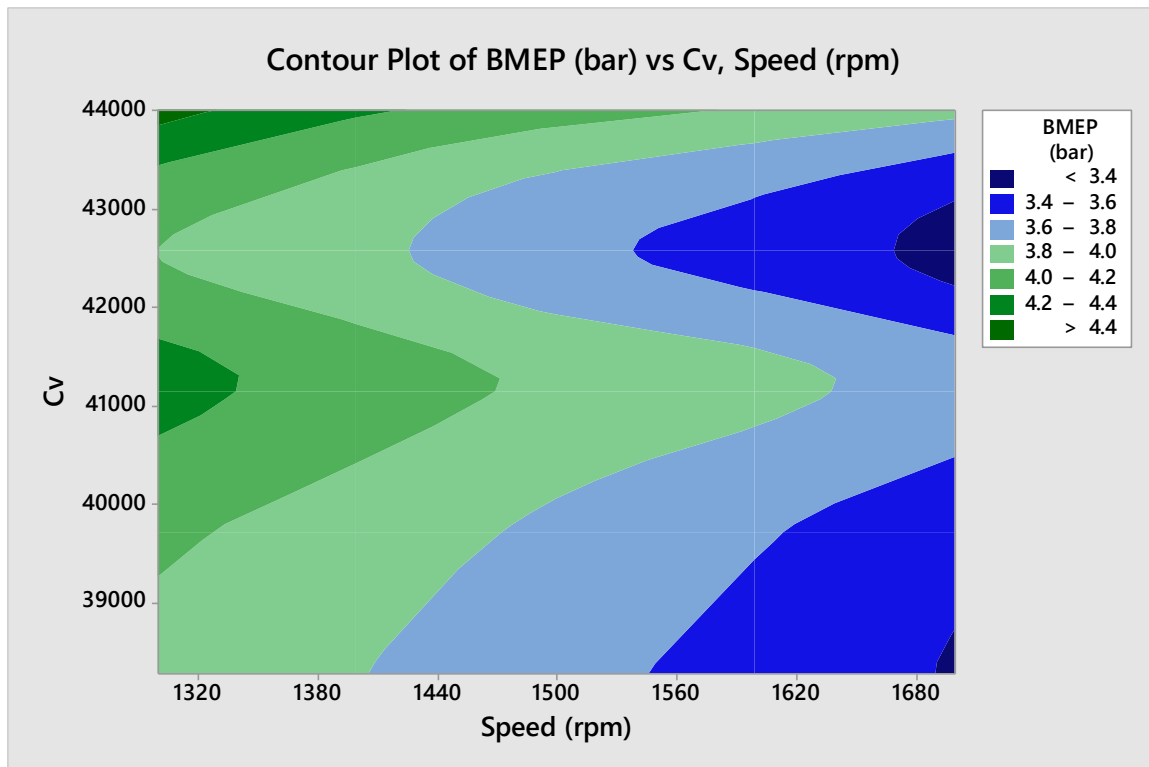


Fig 7 Contour plot of BMEP

It is desirable to have maximum BMEP. Fig 7 gives the contour plot of BMEP. It is seen that BMEP is lower for engine speed more than 1550 rpm and for almost all fuel fractions. Highest values of BMEP are observed for Cv in the range of 40500 to 41500 kJ/kWhr. It is also desirable to operate the engine at lower rpm from 1300 to 1400 rpm.

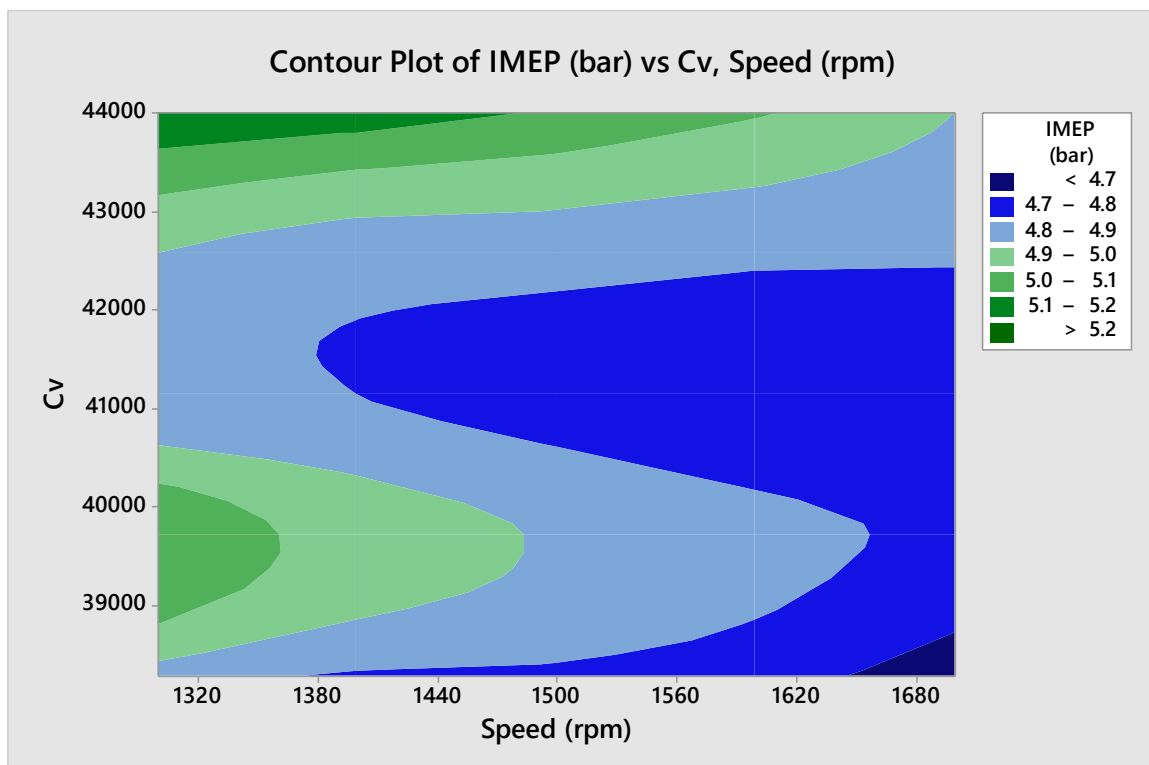


Fig 8 Contour plot of IMEP

Contour plot of IMEP is shown in Fig 8. It is seen that higher values of IMEP are observed only with Cv more than 43000 kJ/kWhr and engine speed 1300 to 1500rpm. This plot also gives important zone of engine operating condition, wherein IMEP values are lowest and this zone must be avoided.

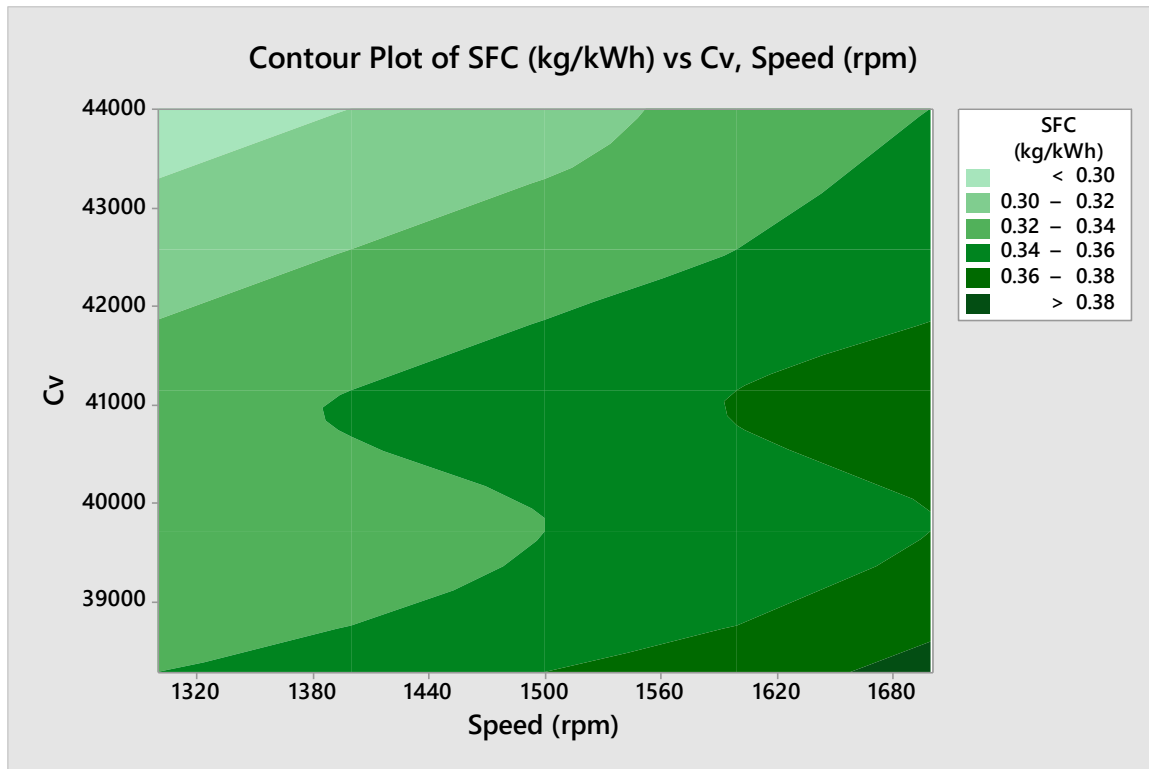


Fig 9 Contour plot of BSFC

BSFC should be lowest for the best operating condition of the engine. The lowest values are observed for operating conditions with Cv 420000 to 44000 kJ/kWhr and engine speed 1300 to 1500 rpm.

3.3 Use of XLSTAT:

XLSTAT is add-on to MS Excel. It provides the statistical solutions to data. In the present study engine is operated at different operating conditions and various engine parameters are recorded. The data generated need to be analysed for finding the optimum performance of the engine. Also it is required to find the relationship of various parameters with each other.

XLSTAT provides various solutions for statistical analysis of the data. It is used in the present study for Analysis of Variance (ANOVA). Multiple regression is also done. A sample case study of one parameter BP is presented here.

Table 1 Correlation Matrix for BP

	Cv	Speed (rpm)	Comp Ratio	BP (kW)
Cv	1	0.000	0.000	0.610

Speed (rpm)	0.000	1	0.000	0.510
Comp Ratio	0.000	0.000	1	0.563
BP (kW)	0.610	0.510	0.563	1

Table 1 gives the correlation matrix for BP. Three operating parameters Cv, speed and CR are related to BP with the correlation coefficients of 0.61, 0.51 and 0.563 respectively. This matrix gives the weightage of each independent variable.

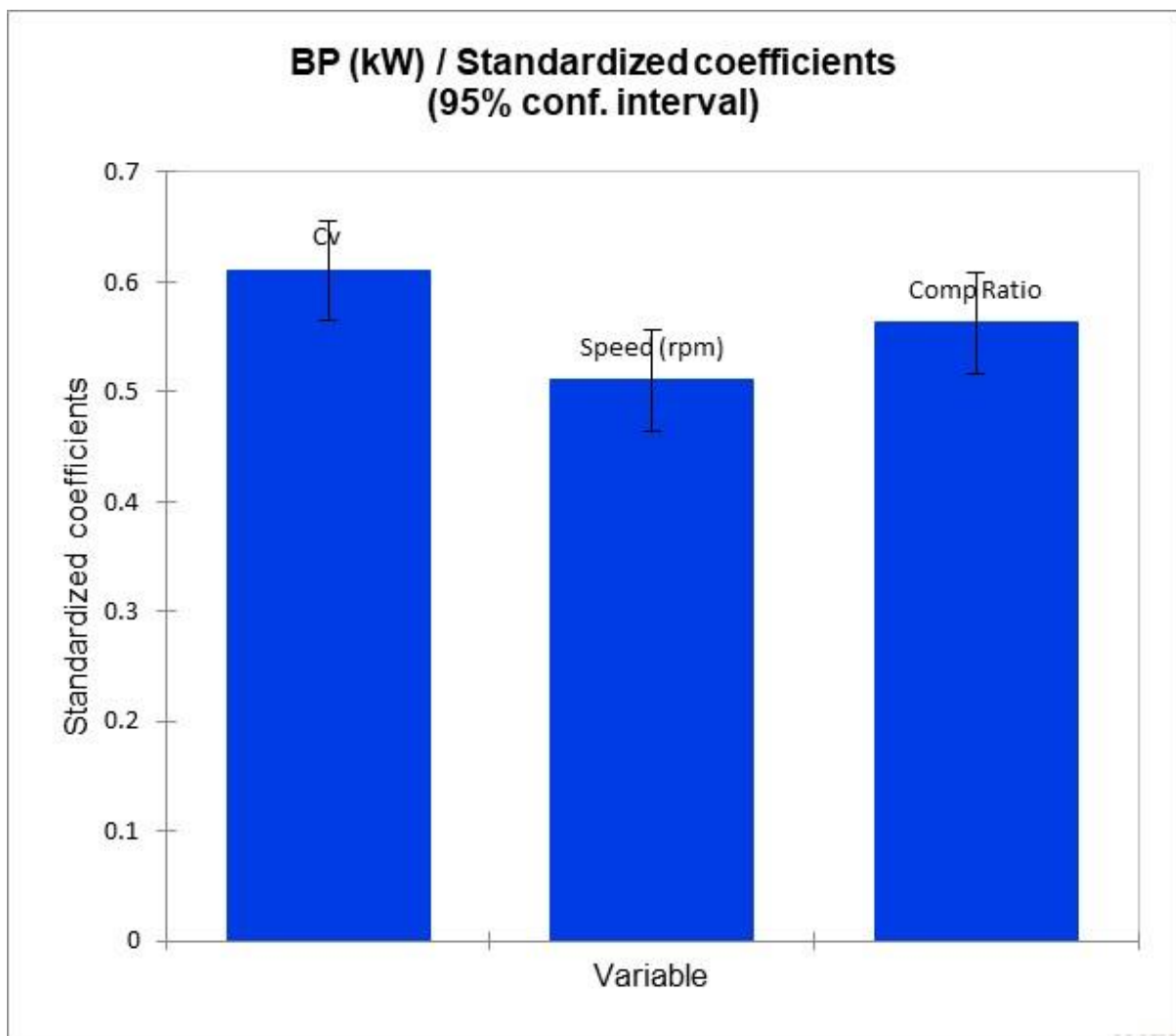


Fig 10 Standard Coefficients of BP

Influence of three independent variables on BP is shown in Fig 10. The values from Correlation matrix are plotted by XLSTAT automatically in the graphical form. From Fig 10 it is noted that Cv has the maximum impact on BP and engine speed has the lowest impact on BP.

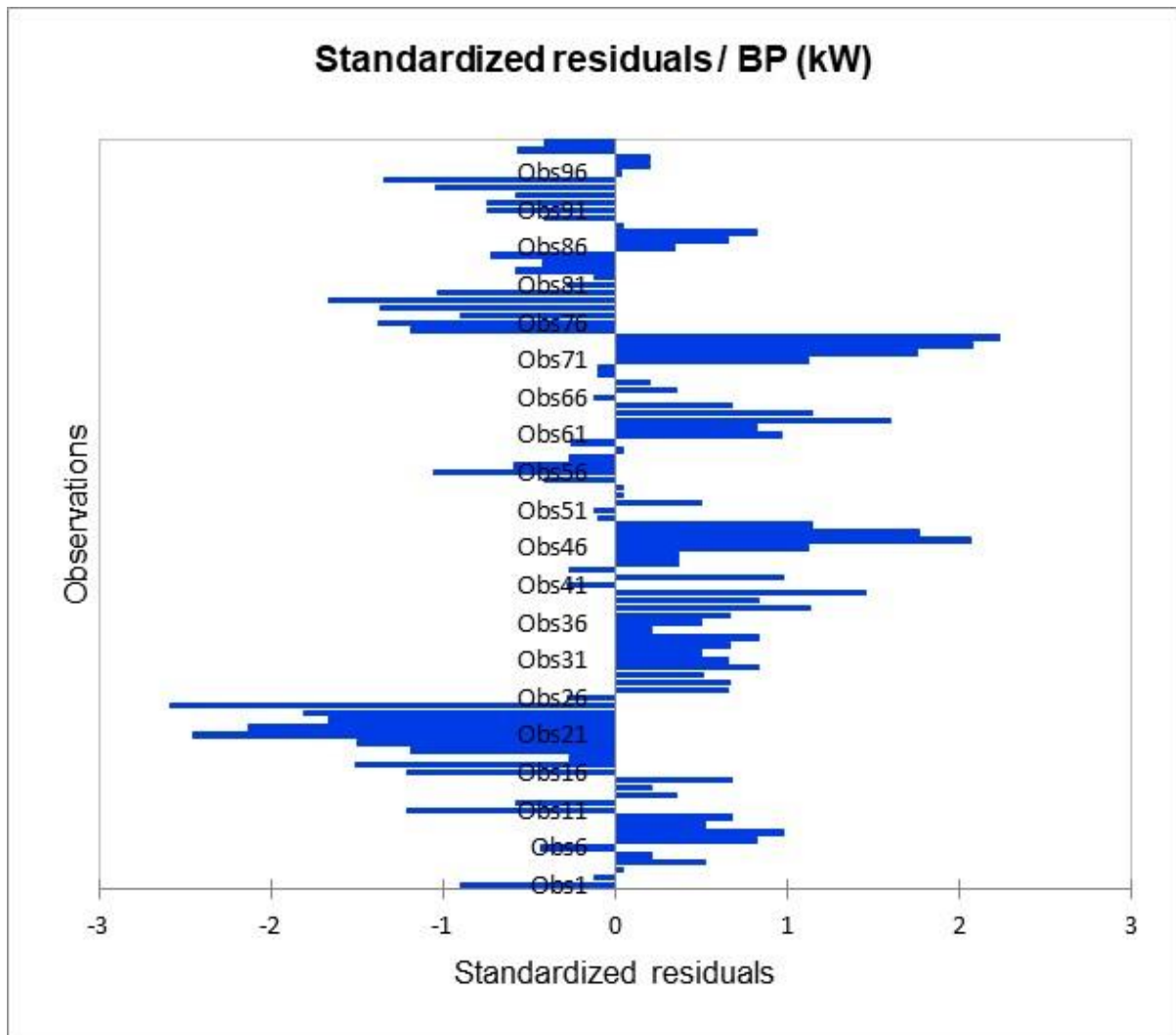


Fig 11 Standardised residuals for BP

Standardised residuals in the process of regression analysis is plotted in Fig 11. This plot is a unique representation by XLSTAT. It is noted that the residuals are distributed on both negative and positive directions and within the limits.

4 Conclusions:

Prediction of engine performance is possible with different methods like using standard correlation equations, mathematical models or empirical relations. It is required to establish the relationship of dependent and independent variables for any given operating conditions. Mathematical models and established correlations are used only for predefined set of input parameters and it is not possible to use standard equations for exact predictions of engine parameters. Minitab 17 provides various tools like different types of regression analysis. This helps in framing the mathematical equations and also provides the accuracy of the equations developed. In the present study large errors up to $\pm 20\%$ are observed for BSFC. The errors may be due to the assumption that linear relationship exist in the given parameters. It is required to develop the accurate relations, with new assumptions of type of possible equations like quadratic, logarithmic or any suitable form. For other parameters the equations generated are accurate and percentage errors are in the range of $\pm 10\%$.

XLSTAT gives more advantages over Minitab 17 in terms of graphical correlations, residue plots, standard residues and also the graphical relations of actual Vs predicted values. Graphical representation provides sufficient and necessary information to take the decisions of equation accuracy and optimised performance zones. It also gives different matrices for observing the impact of each independent variable over dependent variables.

Using computational tools helps in framing the correlations, developing mathematical models, graphical representation of the data. Various statistical operations like ANOVA, design of experiments, regression analysis can be done using computational tools.