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Prediction on Combustion Pattern of CNG-Diesel Duel Fuel Engine Using Response Surface Methodology

Muhammad Shahfirul Kota[1], Abd Fathul Hakim Zulkifli[1]*

[1]Department of Mechanical Engineering Technology, Faculty of Engineering Technology,
Universiti Tun Hussein Onn Malaysia, 84600 Pagoh, Johor, MALAYSIA

*Corresponding Author Designation

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Abstract: Application natural gas in dual fuel system is considered to be a potential alternative to conventional fossils fuels for vehicles application due to its lower greenhouse gas emissions and availability. However, the conversion process for duel fuel system is challenging. The main objective for this study is to predict the combustion pattern of Compress Natural Gas (CNG)-Diesel dual fuel engine using Response Surface Methodology (RSM). Two inputs, which are CNG fraction (0.00 %, 10.00 %, 20.00 %, 30.00 % and 40.00 %) and engine speed (1500, 2000, 2500, 3000 and 3500 rpm) were used to predict engine output characteristics based on combustion pattern. The evaluation of combustion characteristic in term of ignition delay (ID), peak in-cylinder pressure (PP), heat release rate (HRR) and combustion duration (CD). 10 numbers of runs were computed using Design Expert software with average error of 0.40 %. The surface response analysis showed that the rate of substitution of CNG and its characteristics influence the engine output characteristics significantly. The prediction model for ID was suggested was linear model while PP, HRR and CD was suggested 2FI model. Using a confirmation test, the prediction models were validated and showed good predictability within the 95.00 % confidence interval. Hence, it is concluded that RSM provides prediction models with significant accuracy that predict combustion pattern, contributing to the efficiency of the conversion process for diesel-CNG dual fuel engines.

Keywords: CNG-Diesel Dual Fuel Engine, Response Surface Methodology, Combustion Pattern, Prediction Model

1. Introduction

CNG has a strong ability to replace conventional diesel and petrol fuels. However, application on existing diesel engine is difficult as it needs a source of ignition to be combusted. In addition to installing the ignition and gas fuel system, there is a need for adjustment of the compression ratio to cope with the fuel properties. So, we preferred to applied Diesel-CNG Dual Fuel (DDF) system

Corresponding author: fathul@uthm.edu.my

without any adjustment on existing diesel engine. CNG is pumped directly into the intake manifold, and a certain volume of diesel fuel is ignited [1]. The conversion can be made by installing a gas fuel system on the diesel engine without affecting physical components of the original system and engine.

Preceding research, studies have reported that DDF combustion has great potential to reduce more than 20.00 % of CO_2 emission [2] [3]. This is because among other hydrocarbons, the natural gas has the lowest carbon content. Thus, DDF engine combustion is cleaner and yields less CO_2 emission compared to other petroleum fuels. In actual practice, high fuel consumption and emissions were shown by DDF engine at higher capacity engine operation, particularly at 1500 up to 3000 rpm [4]. It may be resulted by uncontrolled blending ratio between diesel and CNG fuel.

Currently, diesel engines are widely used in a variety of applications. Many efforts have been tested and developed to overcome some of the barriers in terms of engine thermal efficiency due to fuel-air combustion, which releases heat converted to useful power output and exhaust gas emissions. Under this scenario, the fuel and air mixture is heterogeneous, requiring further improvement of the air insertion into the fuel jet spray and the spread of fuel over air-occupied space. To address this obstacle, the diesel dual fuel (DDF) engine is one of the promising technologies to promote more homogeneous pre-mixed charges by adding a relatively low cetane number of fuel prior to compression and ignition of the main diesel fuel. This increases the benefits in many facets, depending on the type of fuel and the operating conditions. A number of publications have been published on DDF engines using gaseous fuel pre-mixtures such as compressed natural gas (CNG), liquefied petroleum gas (LPG), hydrogen (H2) and biogas [5]. Among other gaseous and liquid fuels, gasoline is one of the promising fuels for DDF combustion, as it is readily available on the market [6].

In this research, the Response Surface Methodology (RSM) is used to predict the relation between the rate of fuel substitution and the characteristics of engine output in term of combustion pattern. The design of the experiment using RSM could provide an experimental method for predicting combustion pattern responses. In addition, through its contour plot and response surface profile, these response characteristics can be presented graphically, which are useful for establishing response values and operating conditions as required. The modeling methodologies are capable of predicting with significant accuracy the untested conditions as reported by [7 – 9]. The objective of this study to analysis in-cylinder pressure signals of CNG-Diesel Dual Fuel Engine and investigate its combustion pattern. The dual fuel set ratios are targeted at 0.00 %, 10.00 %, 20.00 %, 30.00 % and 40.0 % of diesel replacement in term of mass ratio within the operating range of 1500 to 3500 rpm engine speeds. The evaluation of combustion pattern is based on ignition delay (ID), peak in-cylinder pressure (PP), heat release rate (HRR) and combustion duration (CD).

2. Materials and Methods

The methodology of the research is described in this section. For Response Surface Methodology (RSM) analysis, the experimental and numerical approach is combined. Numerical approach for design of experiment based on pre-determined input and output variables. Experimental work is then carried out on the basis of steady state dynamometer testing for diesel and dual fuel mode. For RSM analysis, four output variables are used to develop prediction models and characterizations of diesel-CNG dual fuel combustion pattern which are ignition delay (ID), in-cylinder peak pressure (PP), heat release rate (HRR), and combustion duration (CD). Then, the contour plot and response surface profile is presented and discussed. The confirmation test was used to validate the prediction model.

2.1 Response Surface Methodology (RSM)

The Design Expert Version 11 software was used for RSM analysis. The input and output variables are shown in Table 1.

Table 1: Input and Output variable for design of experiment

Input	**Unit**	**Low Level**	**High Level**
Engine Speed	rpm	1500	3500
CNG Fraction	%	0	40
Output	**Name**	**Units**	**Remark**
R1	ID	CAD	Crank Angle
R2	CD	CAD	Crank Angle
R3	HRR	J/CAD	
R4	PP	MPa	

The suggested number of runs for the experiment was 10 runs consisting of the required 6 model points and 4 replicate points as shown in Figure 1.

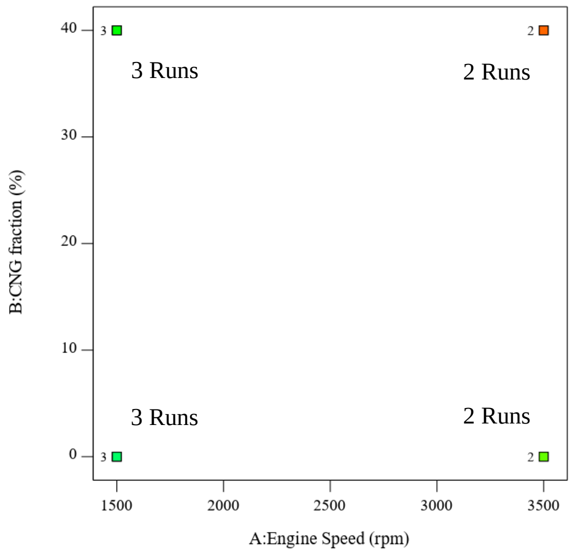


Figure 1: Number of runs required for experimentation

At engine speed 1500 rpm with 0.00 % and 40.00 % of CNG fraction (3 data point) each of them and also at engine speed 3500 rpm; 0.00 % and 40.00 % CNG fraction (2 data point) respectively. These 10 data points are analysed by using the second-order model term to evaluate the design model. This evaluation is carried out via prediction variance through fraction design space (FDS) plot. The FDS plot provided a graphical evaluation of the distribution of the prediction variance over the design space. Figure 2 shows the mean standard error for a fraction of the design space. The average standard error mean is 0.430 with minimum error and the maximum standard error is 0.316 and 0.707, respectively. FDS is a great tool for comparing response surface design in terms of its potential prediction performance [10]. The ideal FDS plot would be flat with a small prediction variance value.

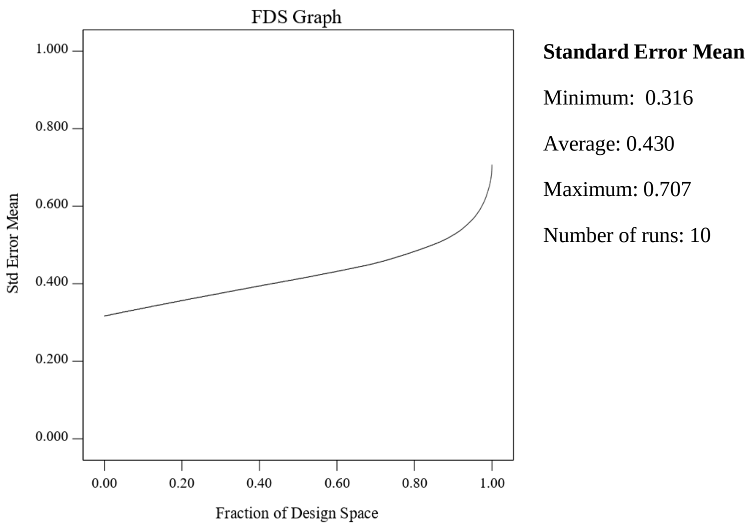


Figure 2: Fractional of design space for response surface design with minimum 10 number of runs

2.2 Experiment Setup

The test engine is Toyota Hilux 2.5 L common-rail diesel with a direct fuel injection system (engine model: 2KD-FTV). It has four-cylinder (in-line), four-stroke and 16 valves (double overhead camshaft). The engine was converted in dual-fuel system using GI GASITALY CNG-Diesel dual fuel kit (Model: GASITALY F5 DGS Diesel/CNG). The conversion process followed the Malaysia legislation and further discussed in [12]. No modification was made on the stock ECU from the original diesel engine. However, minor modification has been made to the dual fuel conversion kit system to be suit the existing engine. The main engine specification is showed in Table 2.

Table 2: Specification on Toyota Hilux 2.5 L common rail direct injection diesel engine

Engine Specification	Description
Engine Code	2KD-FTV
Bore x Stroke	92.0 x 93.8 mm
Engine Displacement	2494 cc
Compression ration	17:4:1
Fuel injection system	Common rail direct engine
Maximum power	80kW @ 3600 RPM
Maximum torque	325 Nm @ 2000 RPM

The Dynapack 4WD chassis dynamometer has been used. The CNG flow rate is monitored by using the ALICAT Scientific Mass Flow Meter (M-250SLPM). Electronic control unit (ECU) Diagnostic Bosch KTS 570 and observed several engine conditions such as engine speed, calculated engine load, coolant temperature, manifold air pressure and accelerator pedal position. In-cylinder pressure measurement is acquired by using Kistler pressure transducer (type 6056a) and amplified by (type 5018a).

The DEWETRON encoder instrument (CA - RIE 360) was used to generate the TDC and clock signals. Both signals are conditioned by DEWETRON with DEWE - Crank angle –CPU. The Compact DAQ (NI-cDAQ 9188) and NI Combustion Analysis System (LabVIEW environment) are used to record data. It is connected to the crank angle encoder; it synchronizes in-cylinder pressure signal in the crank angle domain. The commercial refueling station provided fuel resources for experimentation and the fuel properties shown in Table 2. The experiment setup is illustrated in Figure 2.

Table 2: Properties of fuel [13]

Property	Diesel	CNG
Flash point (PM, °C)	76	-
Kinematic Viscosity (40 °C, Sulfur (mg/kg)	3.21,7.5	-
Cetane index	52	-
Density (15°C kg/m^3)	831	-
Low heating value (MJ/kg)	43.15	-
Gross heating value (MJ/Sm^3)		39.2
Specific gravity compare to air		0.6042
`Flammability limit		5-15
Compressibility		0.9977
Methane (vol.%)		93.07
Ethane (vol.%)		
Ethane (vol.%)		3.70
Propane (vol.%)		0.90
i-Butane (vol.%)		0.29
i-Pentane (vol.%)		0.07
n-Butane (vol.%)		0.13
C_{6+} (vol.%)		0.07
Nitrogen (vol.%)		0.68
Carbon dioxide (vol.%)		1.10

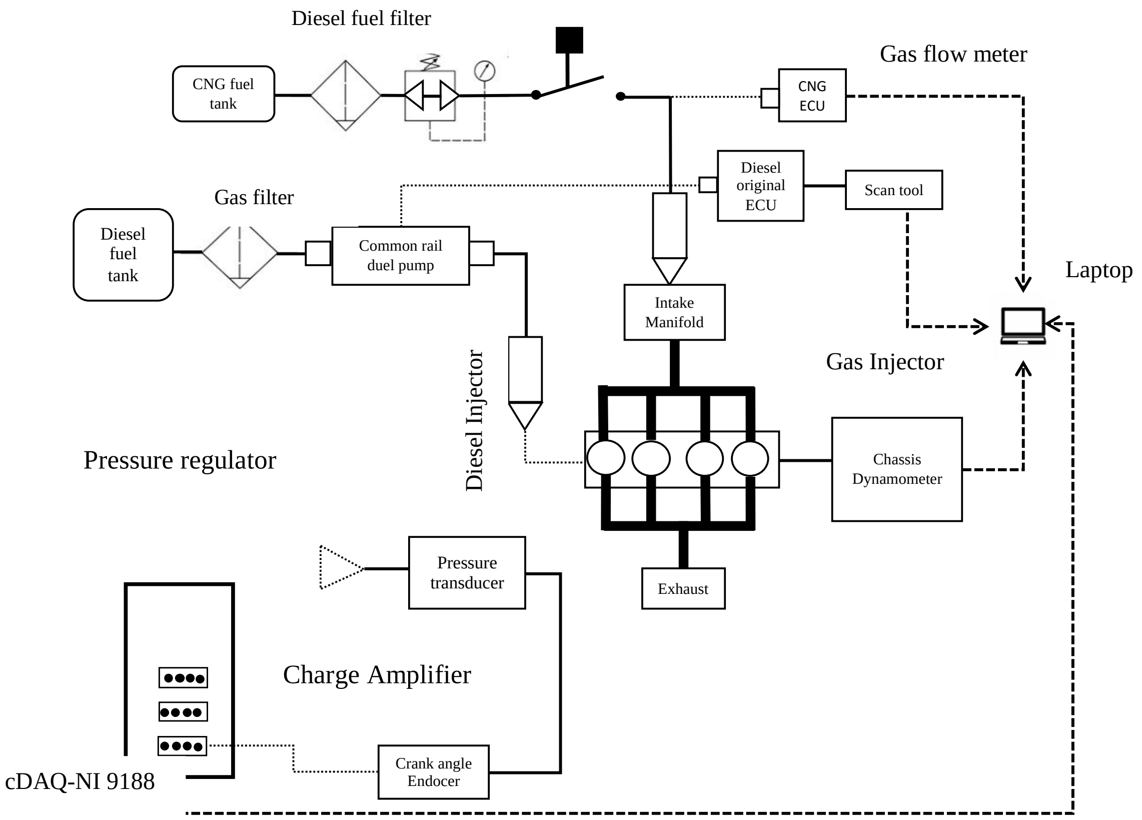


Figure 2: Schematic Diagram for experiment Setup

2.2.4 Uncertainty Analysis

The accuracy of the measuring parameters and the error associated with each measured parameter are determined by comprehensive analysis of uncertainties. The overall uncertainty ($U_{overall}$) for the experimental results is examined by combining systematic uncertainty (S_u) and random uncertainty (R_u) using the root-sum-square method (RSS) with a 95 percent confident level of true value (refer to equation 1 and 3) [10- 12].

Based on equation 2 and 3, M is the physical parameters dependent on each variable, X_i. The S_i and R_i represent the uncertainty in M and the measuring range respectively. The overall uncertainty obtained for the experiment is ± 0.43 percent. The uncertainty for each measurement parameter is summarized in Table 3.

$$U_{\text{overall}} = \sqrt{{S_u}^2 + {R_u}^2} \qquad (Eq.1)$$

$$\frac{S_u}{M} = \left[\sum_{i=1}^{n} \left\{\frac{1}{M}\frac{\partial M}{\partial X_i} S_i\right\}^2\right]^{1/2} \quad (Eq.\ 2)$$

$$\frac{R_u}{M} = \left[\sum_{i=1}^{n} \left\{\frac{1}{M}\frac{\partial M}{\partial X_i} R_i\right\}^2\right]^{1/2} \quad (Eq.\ 3)$$

Table 3: Accuracy and uncertainty of measured parameters

Equipment/ Instrument	Measured parameter	Range	Accuracy	Uncertainty (%)	Remark
Chassis dynamometer	Engine rpm	-	-	-	Engine braking for constant speed
Gas Flow meter	CNG flow rate	0-250 splm	±0.2%	±0.08	
Pressure Transducer	In-cylinder pressure		± 0.1 MPa	±0.05	
Crank angle encoder	Crank angle degree	0 – 360^o	± 1^o	±0.3	

3. Results and Discussion

3.1 Prediction model based on Design of Experiment (DoE) analysis

An illustration of the development of prediction models based on process flow shown in Figure 3. The selected model was tested using Analysis of Variance (ANOVA). The ANOVA assesses the model selected and looks for an overall model term p-value that is less than 0.05, the difference between Adjusted R^2 (R^2_{Adj}) and Predicted R^2 (R^2_{Pred}) is less than value 0.2, the Adequate Precision (AP) value is greater than 4 and insignificant of Lack of Fit (LOF). Predicted R^2 used to evaluate of how well the model estimates a response value. Adjusted R^2 is to the number of model parameters compared to the number of design points. The LOF is the amount missed from the observations by the model predictions. The AP is a ratio of signal-to-noise. It compares the range of the predicted values to the average prediction error at the design points.

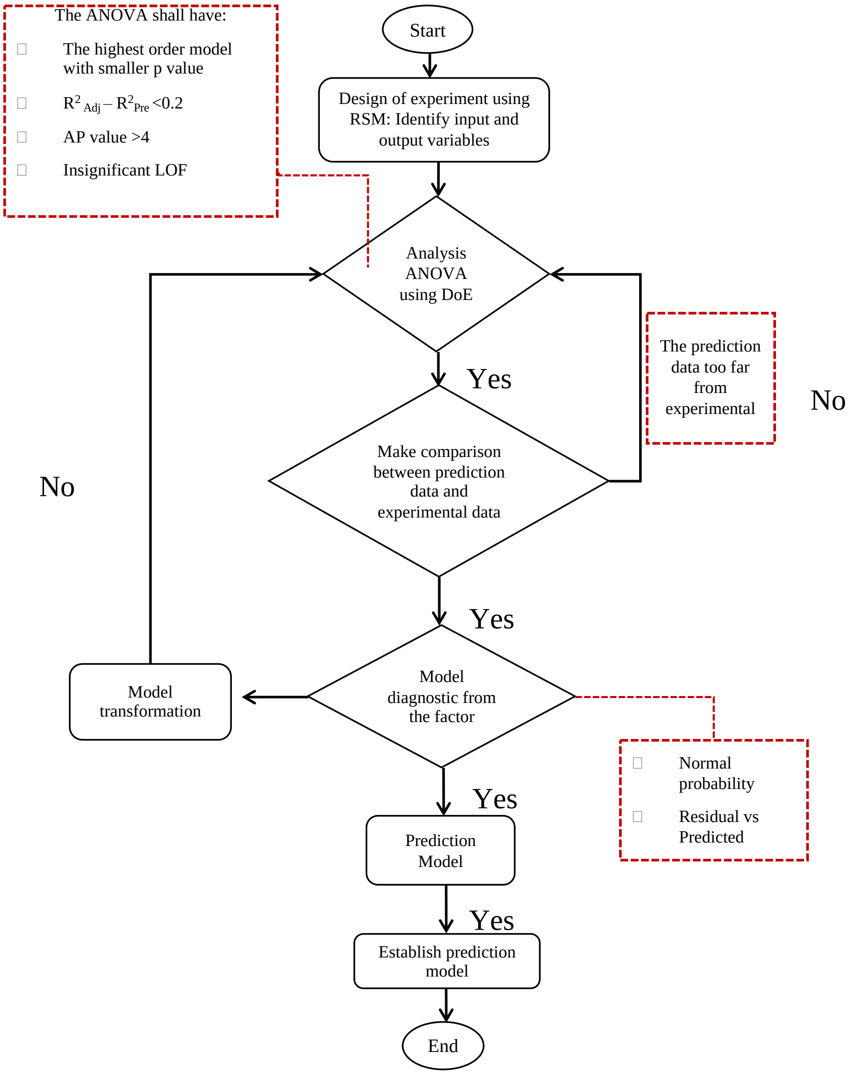


Figure 3: The process of flow chart for development prediction model

3.2 Combustion Pattern

3.2.1 Prediction model for Peak Pressure (PP)

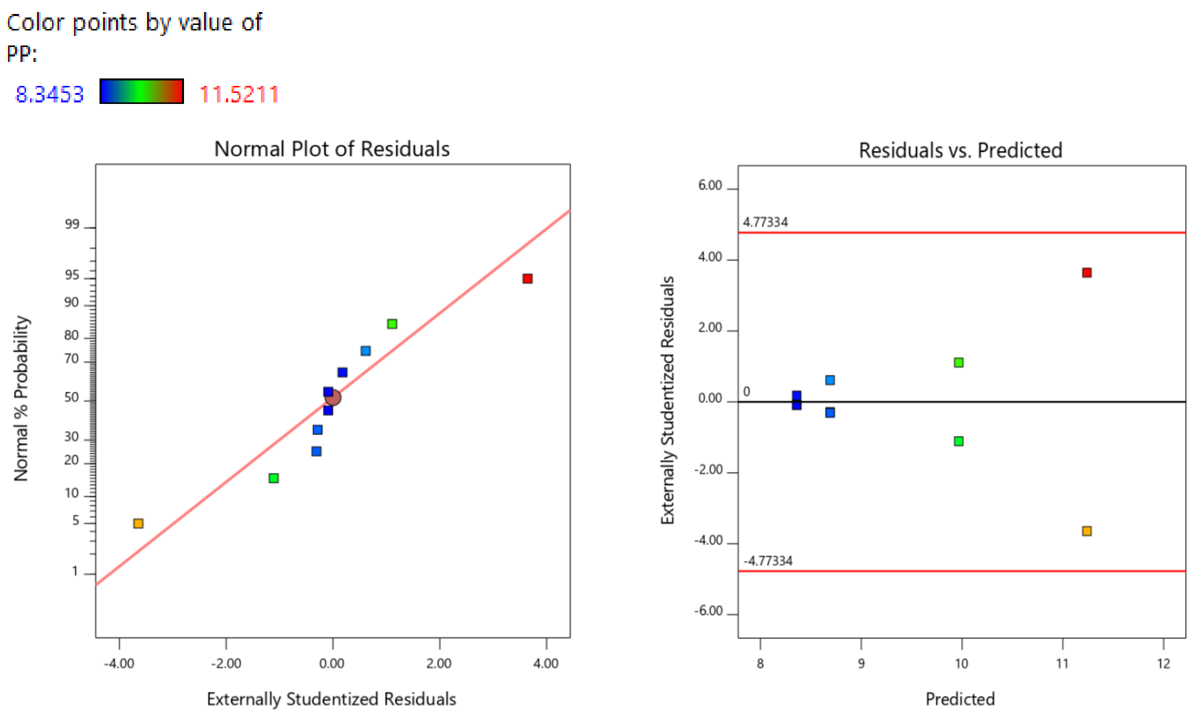
The prediction model for PP suggested with two factor interaction (2FI) model. The p-values of the model are less than 0.005. The difference between Adjusted R2 and Predicted R2 is less than 0.2 and the adequate precision (AP) value is 23.8885, which is greater than 4. The ANOVA table for PP as shown in Table 3.2 and equation is presented in equation 4.

$$PP = +6.77982 + 0.001274A + 0.009380B - 0.000012AB \qquad (Eq.\ 4)$$

Table 3: ANOVA Table for peak pressure (PP)

Source	Sum of squares	df	Mean square	F-value	p-value	
Model	12.14	3	4.05	111.46	<0.0001	Significant
A-Engine Speed	10.36	1	10.36	285.31	<0.0001	
B-CNG fraction	1.54	1	1.54	42.44	0.0006	
AB	0.5316	1	0.5316	14.64	0.0087	
Pure Error	0.2179	6	0.0363			
Cor Total	12.36	9				

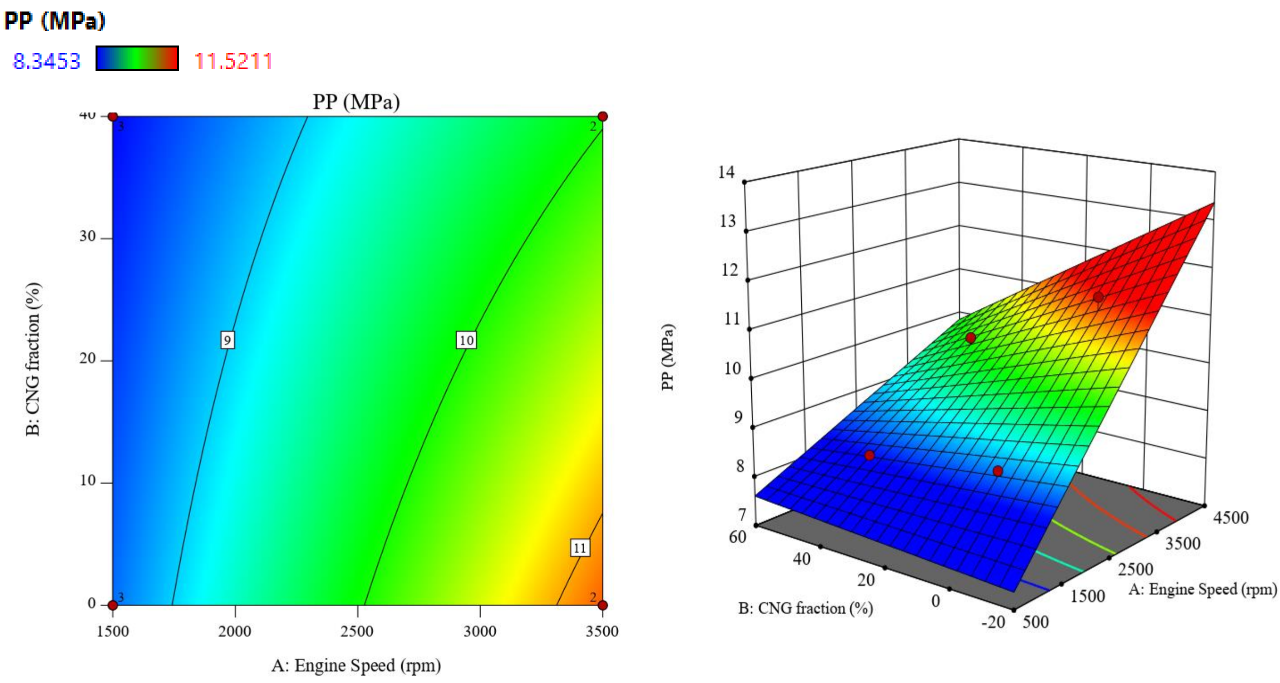
The diagnostic plots for PP models are showed in the Figure 4. The normality of the residues follows a straight line, indicating that the residues are normally distributed. The data is randomly dispersed by the residuals versus predicted plots, which implies that the predicted models are able to navigate within the design space.



(a) (b)

Figure 4: Diagnostic plot for Peak Pressure model (a) Normal plot Residuals (b) Residuals vs Factor

Figure 5 showed the contour plot and response surface profile for PP model. According to the analysis shown as the engine speed increases, the PP has been observed to increase, but the CNG injection minimizes the pressure of the in-cylinder that showed in Figure 3.6. The maximum pressure affected by the amount of CNG injected during ID and the rapid combustion period. Due to the higher self-ignition temperature of CNG, with the high CNG flow rates, diesel fuel injection decreases, the cylinder charge conditions did not favors faster pre-mixed combustion. The low pressure of combustion contributes to this phenomenon.



(a) (b)

Figure 5: The contour plot (a) and response surface profile (b) for PP model

3.2.2 Prediction model for ignition delay (ID)

The prediction model for ID suggested with linear model. The p-values of the model are less than 0.005. The difference between Adjusted R2 and Predicted R2 is less than 0.2 and the adequate precision (AP) value is 18.0944, which is greater than 4. The ANOVA table for ID as shown in Table 3.2 and equation is presented in equation 5.

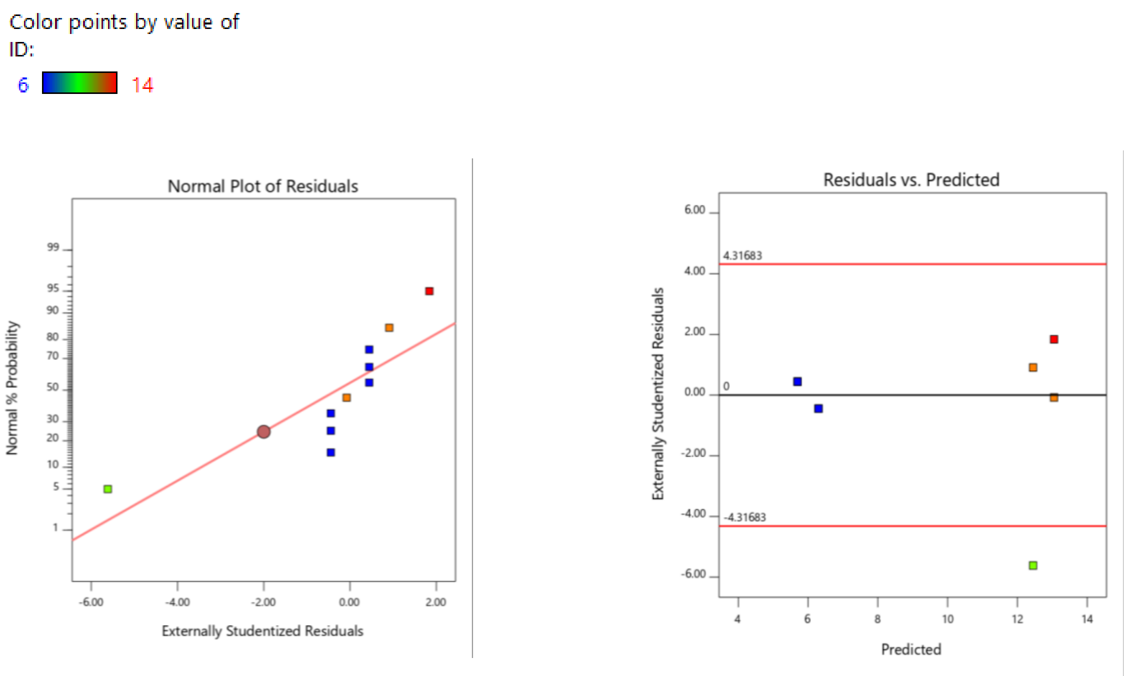
$$ID = +1.23750 +0.003375A -0.015000B \qquad (Eq.\ 5)$$

Table 4: ANOVA Table for ignition delay (ID)

Source	Sum of squares	df	Mean square	F-value	p-value	
Model	110.25	2	55.13	100.23	<0.0001	Significant
A-Engine Speed	109.35	1	109.35	198.82	<0.0001	
B-CNG fraction	0.9000	1	0.9000	1.64	0.2416	
Residual	3.85	7	0.5500			
Lack of Fit	1.35	1	1.35	3.24	1.220	Not significant
Pure Error	2.50	6	0.4167			
Cor Total	114.10	9				

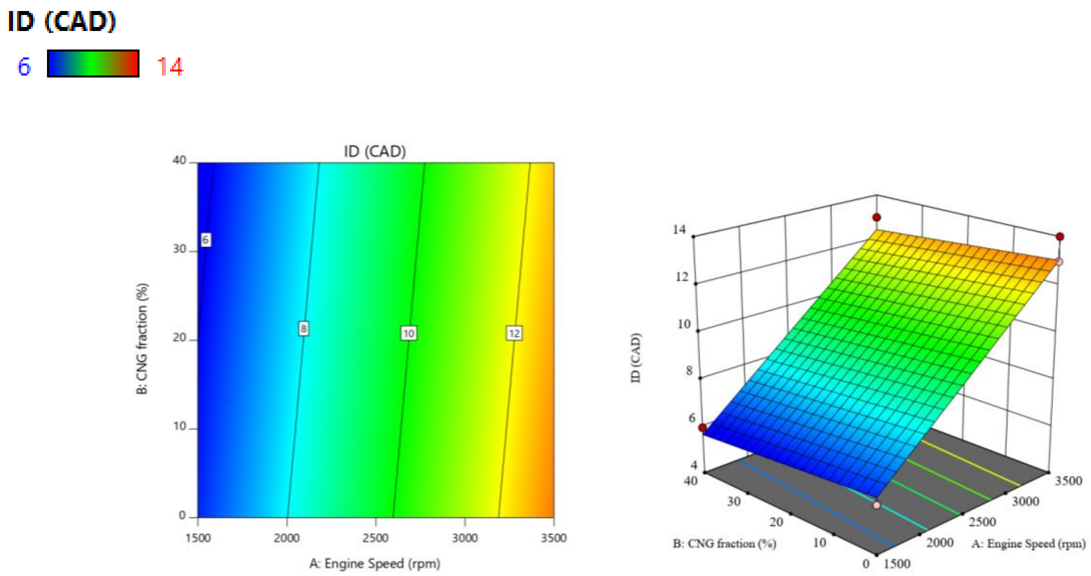
The diagnostic plots for ID models are showed in the Figure 4. The normality of the residues follows a straight line, indicating that the residues are normally distributed. The data is randomly dispersed by the residuals versus predicted plots, which implies that the predicted models are able to navigate within the design space.

The response surface profiles (a) and contour plot (b) for ID model are displayed in Figure 5. Based on the model predicted, the high rate of CNG substitution has delayed the SOC and the ID duration has increased at high engine speed. The low cetane number and high auto ignition temperature of the CNG contribute to the ID period and reduce the burning rate of the combustion phase.



(a) (b)

Figure 4: Diagnostic plot for ignition delay model (a) Normal plot Residuals (b) Residuals vs Factor



(a) (b)

Figure 5: The contour plot (a) and response surface profile (b) for ID model

3.2.3 Prediction model for heat release rate (HRR)

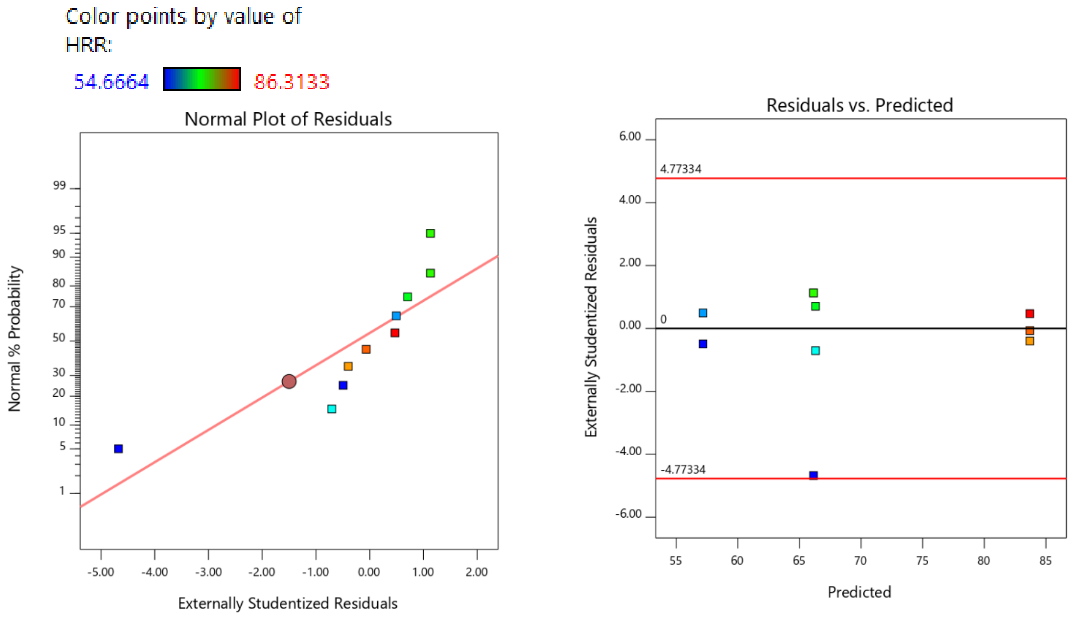
The prediction model for HRR suggested with two factor interaction (2FI) model. The p-values of the model are less than 0.005. The difference between Adjusted R2 and Predicted R2 is less than 0.2 and the adequate precision (AP) value is 6.5883, which is greater than 4. The ANOVA table for HRR as shown in Table 5 and equation is presented in equation 6.

$$HRR = +103.58646 -0.013259B -0.0938899B +0.000333AB \qquad (Eq.6)$$

Table 5: ANOVA table for heat release rate (HRR)

Source	Sum of squares	df	Mean square	F-value	p-value	
Model	962.16	3	320.76	7.92	0.0165	Significant
A-Engine Speed	416.91	1	416.91	10.29	0.0184	
B-CNG fraction	42.55	1	42.55	1.05	0.3449	
AB	426.98	1	426.98	10.54	0.0175	
Pure Error	234.02	6	40.50			
Cor Total	1205.18	9				

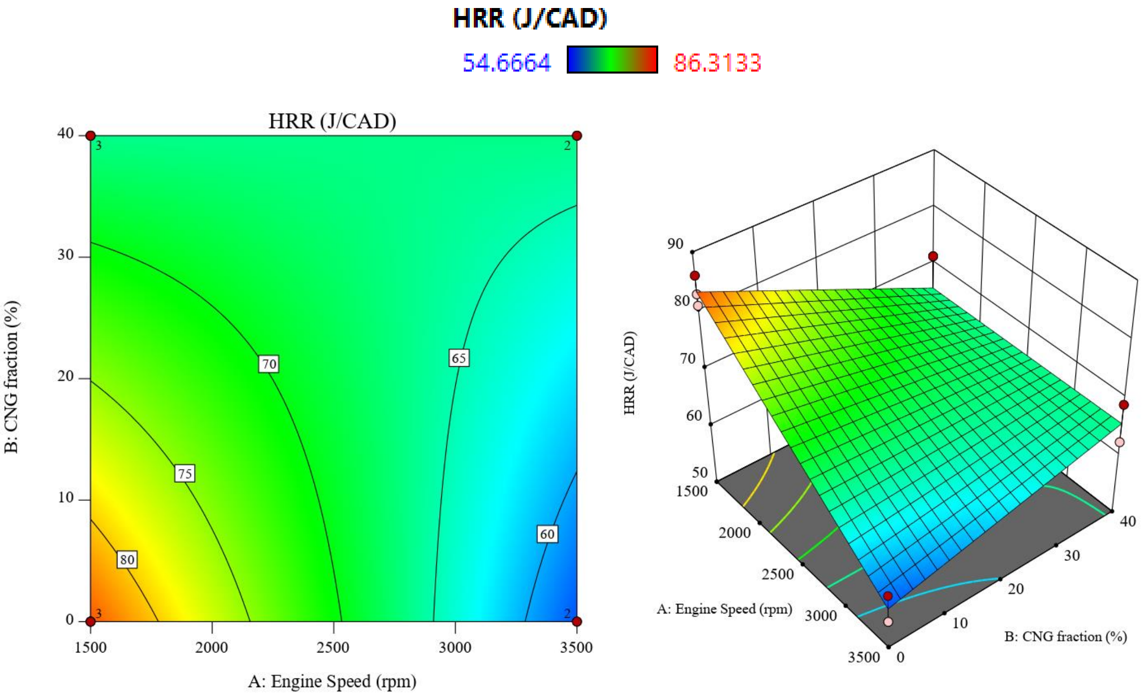
The diagnostic plots for HRR models are showed in the Figure 6. The normality of the residues follows a straight line, indicating that the residues are normally distributed. The data is randomly dispersed by the residuals versus predicted plots, which implies that the predicted models are able to navigate within the design space.



(a) (b)

Figure 6: Diagnostic plot for Heat Release Rate model (a) Normal Plot of Residuals (b) Residuals vs Predicted

Figure 7 presented response surface profile (a) and the contour plot (b) for HRR model. The model showed heat release rate and engine speed as well as the RPM rise in the cylinder of the engine CNG with diesel fuel for the entire range of 0 percent to 40 percent. It can be seen when the CNG energy share increases to 40 percent, the highest of HRR are observed. Nevertheless, low HRR was detected at high engine speed in diesel mode. Technically, high engine speed would require high mixtures of airfuel. High combustion pressure produces high air-fuel mixtures and leads to a high rate of heat release.



(a) (b)

Figure 7: The contour plot (a) and response surface profile (b) for HRR model

3.2.4 Prediction model for combustion duration (CD)

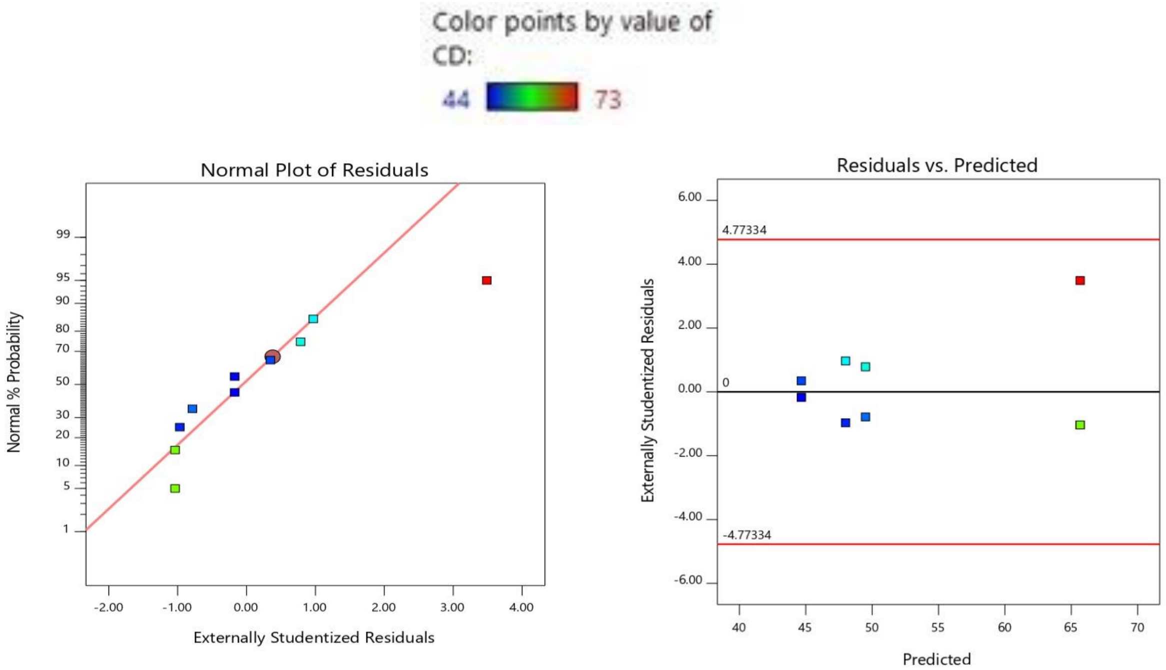
The prediction model for CD suggested with two factor interaction (2FI) model. The p-values of the model are less than 0.005. The difference between Adjusted R2 and Predicted R2 is less than 0.2 and the adequate precision (AP) value is 7.6231, which is greater than 4. The ANOVA table for CD as shown in Table 3.2 and equation is presented in equation 7.

$$CD= +42.16667 +0.001667A+0.890625B -0.000244AB \qquad (Eq.7)$$

Table 6: ANOVA Table for combustion duration (CD)

Source	Sum of squares	df	Mean square	F-value	p-value	
Model	762.57	3	254.19	13.40	0.0046	Significant
A-Engine Speed	98.82	1	98.82	5.21	0.0626	
B-CNG fraction	303.75	1	303.75	16.01	0.0071	
AB	228.15	1	228.15	12.03	0.0133	
Pure Error	113.83	6	18.97			
Cor Total	876.40	9				

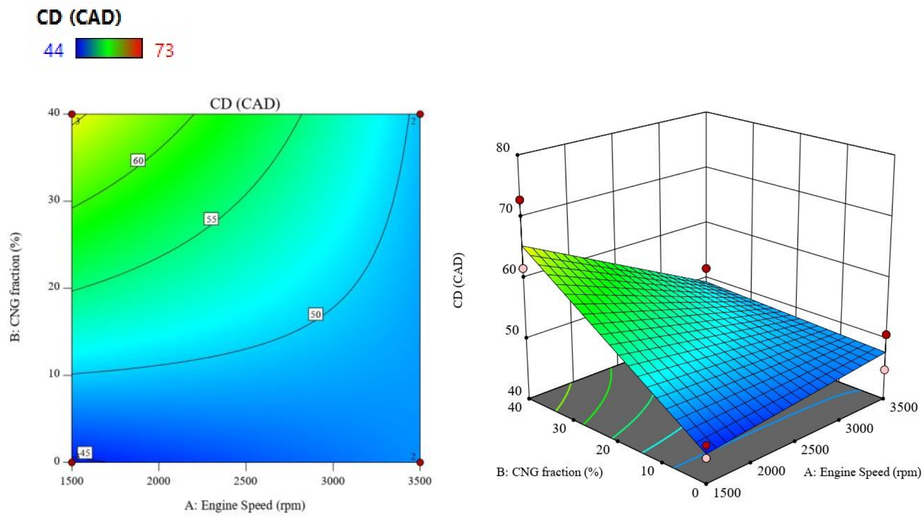
The diagnostic plots for CD models are showed in the Figure 8. The normality of the residues follows a straight line, indicating that the residues are normally distributed. The data is randomly dispersed by the residuals versus predicted plots, which implies that the predicted models can navigate within the design space.



(a) (b)

Figure 8: Diagnostic plot for Combustion Duration model (a) Normal Plot of Residuals (b) Residuals vs Predicted

Figure 9 indicates the response surface profile (a) and contour plot for CD model. The duration of the combustion process is the duration of the combustion process and is the total duration of the flame development and the rapid combustion process. This is the burning duration behavior shows an increase in the burn time as the CNG injection flow rate increases. The highest combustion duration was predicted, approximately at 1500 RPM at 40 percent CNG fraction.



(a) (b)

Figure 9: The contour plot (a) and response surface profile (b) for CD model

3.3 Model Validation

Developed prediction models have been validated by a confirmatory test. The confirmatory test compares the model's prediction interval with the experimental data. It is a simulation of the tuning process. The expected interval is the calculated statistical interval by *Design of Expert* (DoE) software within 95.00 % confident level. 95.00 % PI Low and 95.00 % PI high provide the prediction interval (PI). This is the 95.00 % PI Low means the low value of the forecast interval that will contain the true value of the individual observation 95.00 % of the time, while 95.00 % PI High means the high value of the predicted interval. If the data for the experiment is within the predicted interval, the model will be confirmed. When the prediction model is confirmed, it indicates that it could well predict the developed model. All predicted models in the range of 1500 rpm to 3500 rpm were tested at 0.00 %, 10.00 %, 20.00 %, 30.00 % and 40.00 % CNG substitution rates.

The performance combustion characteristics prediction model for ID, PP, HRR and CD are showed in Figure 3.9 until Figure 13 respectively. Equation that mention earlier which is equation 4 to 7 was used to produce the predicted values. As the experimental data is within the prediction interval, the prediction models demonstrate good predictability. But very few points were observed outside the predicted interval, particularly during the 30.00 % and 40.00 % substitution rates.

Generally speaking, all analysis methods are confirmed because of their ability to assume the patterns of combustion with good precision. Few conditions are considered tolerable for predicted values outside of the prediction interval. Due to the engine's natural characteristics, this could happen. Further analysis explanation according to the model as showed above.

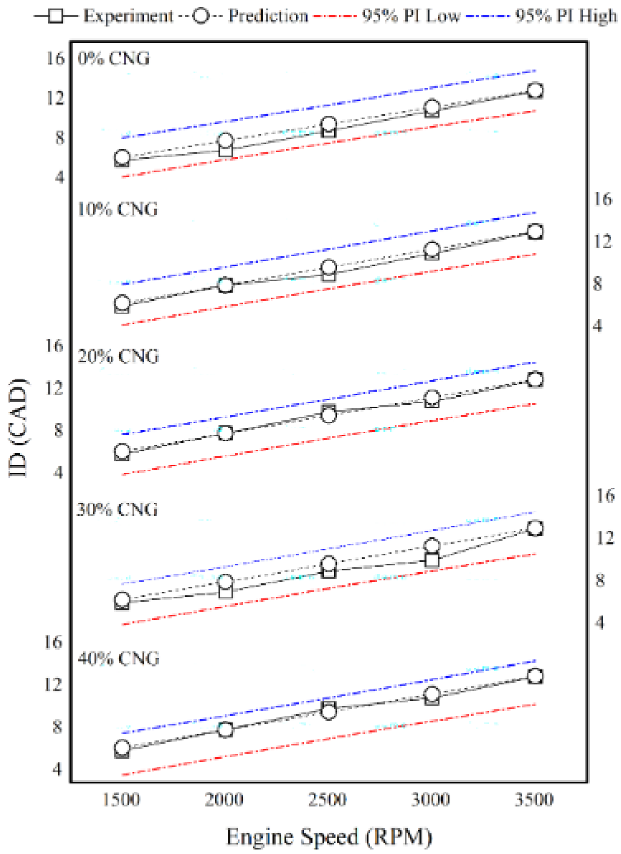


Figure 10: Predicted vs Experiment value for ID model

The confirmation test for ignition delay prediction models are illustrated in Figure 10. The prediction values were calculated by using Equation 4. Based on the view of the model, overall points almost same with experimental data. The prediction models of this response are same as experimental data where one points almost slip from prediction interval which at 2000 rpm and 30.00 % CNG fraction. Generally, all the points of ID model confirmation test were same enough as an experimental data.

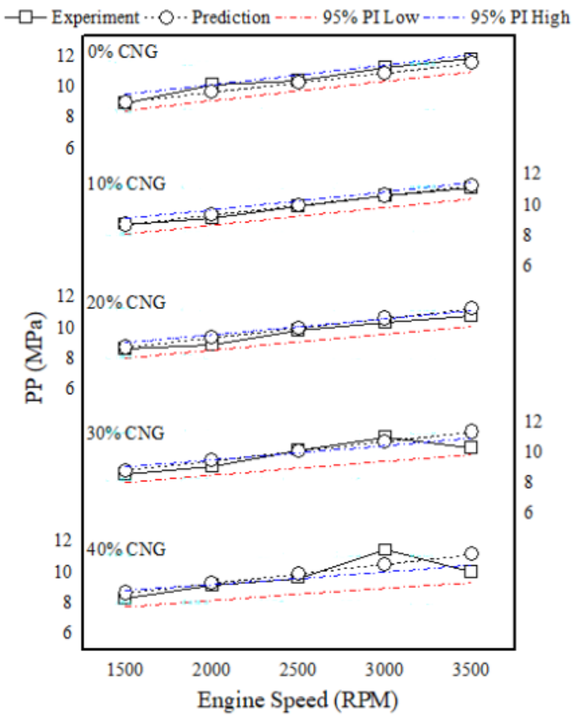


Figure 11: Predicted vs Experiment values for PP model

The confirmation test for PP model is showed in Figure 11. The prediction values were calculated based on equation 5. The experimental results for PP prediction model were within the prediction interval, except for condition engine speed at 3000 rpm and CNG fraction at 40.00 % where the point observed was outside the prediction interval and also other one points at 3500 rpm during same engine speed condition.

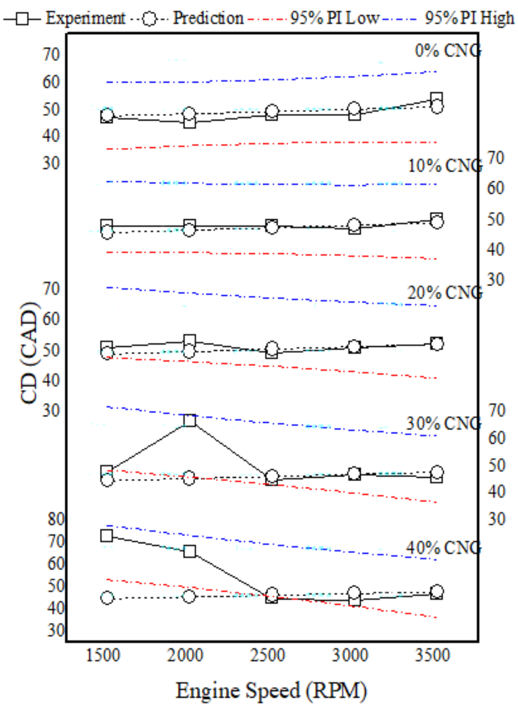


Figure 12: Predicted vs Experiment value for CD model

Figure 12 shows the confirmation test for CD prediction model. The prediction values of model were determined using equation 6. For combustion duration model, three points are outside the prediction interval was observed for CD prediction model. Two points at 2000 rpm of engine speed, during 30.00 % and 40.00 % CNG fraction, respectively. One point at 1500 rpm and 40.00 % CNG fraction showed large scale of difference between prediction data and experimental data.

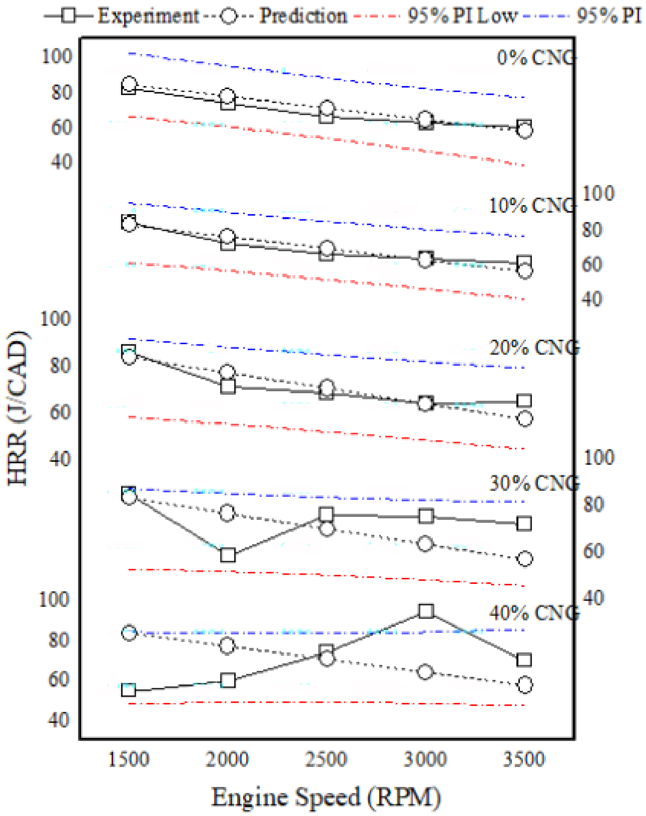


Figure 13: Predicted vs Experiment value for HRR model

Figure 13 showed the confirmation test for heat release rate model. The prediction values calculated using equation 7 as showed in the previous explanation. From the view of the prediction model, a few points were recorded outside the prediction interval especially at 30 per cent and 40 per cent of CNG fraction. At engine speed 2000 RPM in 30 per cent and 40 per cent of CNG fraction there are two points outside from prediction interval due to errors detected. A large difference scale showed at 40 per cent of CNG fraction in 1500 and 3000 RPM respectively. Other than that, two point of 30 per cent at 3000 and 3500 RPM showed a minor scale difference between prediction data and experiment data.

4. Conclusion

The summary of main findings for this analysis is as follows:

i. The prediction model for combustion characteristics prediction models, PP, HRR and CD model was suggested with the two-interaction factor (2FI) model, while ID model linear mode was predicted.

ii. The contour plot and response surface profile produced by RSM analysis showed PP decreased the dual fuel operation and delayed the ID periods. According to the results, it was observed low HRR at low engine speed and increases at high engine speed compared to the experiment data, while CD periods was longer at lower engine speed. This is mainly due to the CNG fuel characteristics, which are high temperatures for self-ignition. The existence of CNG during dual-fuel operation has altered the engine's behavior patterns, where the timing of the injection is delayed.

iii. The validation of the model was performed through the confirmation test where the model was tested. Within its prediction, experiment data was compared to prediction models range interval. 95.00 % PI Low and 95.00 % PI High provide the prediction interval (PI). If the data from the experiment is within the prediction interval, the model is confirmed. The model was tested in the range of 1500 rpm to 3500 rpm at 0.00 % to 40.00 % CNG substitution rates. All prediction models demonstrate good precision and predictability except a few points of CD and HRR model was observed run from prediction interval especially at 30.00 % and 40.00 % of CNG fractions. Although the misplaced observations are tolerable based on the overall performance of prediction models.

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