Optimization Design Parameters of Intake Manifold for Natural Aspirated Engine

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ABSTRACT

*Improving engine performance, reducing fuel consumption costs and decreasing emissions are the primary objectives of vehicle manufacturers. Aware on the fluctuation of the national gas price, an idea had been proposed on improving the air intake system in order to get a good fuel economy and a better engine performance. The purpose of this study is to design new intake manifold on air intake system for the natural aspirated car with the selected parameters of runner length (A), runner diameter (B), plenum Volume (C), and surface roughness (D). Necessary steps have been taken involving the Design of Experiment (DOE) to find the optimum result for all the factors that have been selected by using Box-Behnken design (BBD). The data of torque and fuel consumption are obtained from the 1D Computational Fluid Dynamics (CFD) usingthe AVL Boost software. Within the range studied, the optimized parameters value for the maximum engine performance and minimum fuel consumption was at the A = 200.00mm, B = 33.56mm, C = 0.5L and D = 0.15µm. The maximum engine performance and minimum fuel consumption were determined as 99.541Nm/rpm and 8.8652×10^{-4} kg/s, respectively. Then, the new model of the intake manifold with optimum parameters was developed using NX8.0. Apart from that, polyamide and injection molding had been identified as the best material and manufacturing process for the development of the intake manifold***.**

Keywords: *Intake manifold, response surface methodology, Box-Behnken, fuel consumption, engine performance*

1.0 INTRODUCTION

The automotive industry is currently experiencing pressures due to the fluctuation of petrol price. This is going to be a year unlike many others since the petrol prices are seen continuously fluctuating (rise and fall) [1]. Nowadays, people are more demanding on having a good fuel economy car that can provide a better performance. In Malaysia, it is critical for the drivers, particularly in a town area where people have to constantly face traffic's conditions. Therefore, automobile manufacturers are currently under pressure to provide more environmentally friendly and fuel-efficient car.

Recent studies claimed that air intake system can give a good fuel economy [2]. The design of the engine components, measuring and control methodology of the parameters are very important to improve the engine capabilities [3]. A new improved component in the air intake system can somehow give a good fuel economy and also overcome the unsteady gas price.

Air intake system consist of air cleaner, air flow meter, throttle valve, air intake chamber, intake manifold runner, and intake valve. These components play an important role for the intake system in order to give a good performance to the vehicle. Modification can be made on these components because the performance of the vehicle is also affected by the air intake system. It has also known that the inlet port design and the intake manifold configuration have a direct influence on engine performance [4]. The intake system can be optimized so that it can give more benefits to the owner of the vehicle. Intake manifold is one of the components that can be modified and also plays an important role to ensure a good performance for the engine.

In this study, it will focus more on designing new improved intake manifold on air intake system for the car. Intake manifold is one of the engine components which will improve the efficiency of the engine as well as improve the acceleration of the car [5]. The designing of intake manifold will include some parameters that can give a good fuel economy as well as increase the engine performance. The simulation will fully being run by using *AVLBoost*software and the designing of a new optimized intake manifold will be on *NX 8.0* software. The engine that involve in this study will be naturally aspirated. The engine simulation will correctly draw as refer to the characteristics of natural aspirated engine

2.0 RESEARCH METHODOLOGY

2.1 Levels of Design of Experiment (DOE)

This study starts when the levels of the DOE has been clearly identified based on low level (-1), central point (0) and high level (+1). All these values are from the previous research. The data that been obtained clearly shows that the values had been studied by the researchers but with their specific objective and scope of their study. This study depends on this level of the DOE as it will be the upper and lower limits for modeling in *Design Expert*.

2.2 *Box-Behnken* Design (BBD)

A BBD is a type of response surface design that does not contain an embedded factorial or fractional factorial design. For a BBD, the design points fall at a combination of the high and low factor levels and their midpoints as presented in Table 1.

Table 1: Levels of the DOE

Parameter	Code	Low level (-1)	Central point (0)	High level (+1)
Runner length (mm)	*A*	200.00	240.00	280.00
Runner diameter (mm)	*B*	20.60	34.30	48.00
Plenum volume (L)	*C*	0.50	1.15	1.80
Surface roughness (μm)	*D*	0.00	1.97	3.94

BBD has treatment combinations that are at the midpoints of the edges of the experimental space and require at least three continuous factors [6]. BBDs also ensure that all factors are not set at their high levels at the same time. For this studyusing BBD, a total of 29 experiments has been produced including five central points as presented in Table 2. A mathematical model to calculate the total number of experiments is as follows:

$$N = 2k\,(k - 1) + C_p \tag{1}$$

Where N is the number of experiments, k is the number of factor while C_p is the central point.

Table 2: Design of experiment (DOE)

Run	**Runner length (mm)**	**Runner diameter (mm)**	**Plenum volume (L)**	**Surface roughness (µm)**
1	200.00	34.30	0.50	1.97
2	200.00	34.30	1.80	1.97
3	200.00	34.30	1.15	3.94
4	240.00	20.60	0.50	1.97
5	240.00	34.30	0.50	0.00
6	200.00	34.30	1.15	0.00
7	240.00	34.30	1.80	0.00
8	240.00	34.30	0.50	3.94
9	240.00	34.30	1.15	1.97
10	200.00	20.60	1.15	1.97
11	280.00	48.00	1.15	1.97
12	240.00	48.00	1.15	3.94
13	240.00	34.30	1.80	3.94
14	200.00	48.00	1.15	1.97
15	240.00	48.00	1.15	0.00
16	240.00	48.00	1.80	1.97
17	240.00	34.30	1.15	1.97
18	280.00	34.30	1.15	3.94
19	240.00	34.30	1.15	1.97
20	280.00	34.30	1.80	1.97
21	280.00	34.30	1.15	0.00
22	240.00	34.30	1.15	1.97
23	240.00	48.00	0.50	1.97
24	240.00	20.60	1.80	1.97
25	280.00	20.60	1.15	1.97
26	240.00	20.60	1.15	3.94
27	240.00	34.30	1.15	1.97
28	280.00	34.30	0.50	1.97
29	240.00	20.60	1.15	0.00

2.3 Steepest Descent

The objective of the steepest ascent method is to move to the optimum region using the most efficient route, namely, using the minimum number of experiments. Generally, first-order regression model is sufficient for the current operating conditions [7]. For this study, this method was applied to determine the lowest possible value for the fuel consumption, the relevant equation of which is based on the steepest descent method as follows:

$$(\Delta x_i/\beta_i) = (\Delta x_j/\beta_j) \tag{2}$$

Where Δx is equal to the step size and β is equal to the highest coefficient of the coded value.

2.4 Design of Experiment

A total of 29 experiments is presented in the so-called*Experimental Matrix Design*. Usually the data was arranged according to the number of runs. These experiments consist of different values. For the response column, there is no data listed. This is because we must obtain the data from the simulation. A total of 29 runs will be simulated in *AVL Boost* software. The suggested values of all the four factors will be used to run the simulations.

2.5 Engine Simulation

The final drawing of the engine component on *AVL Boost* software that illustrates the 1D CFD is shown in Figure 1. The data from the experimental matrix design was used to run a complete simulation. All the suggested values were set into the engine simulation according to their elements. Only the elements involve in designing the intake manifold will be reset while others remain as the standard default value (initial state). A total of 29 runs was executed for this procedure.

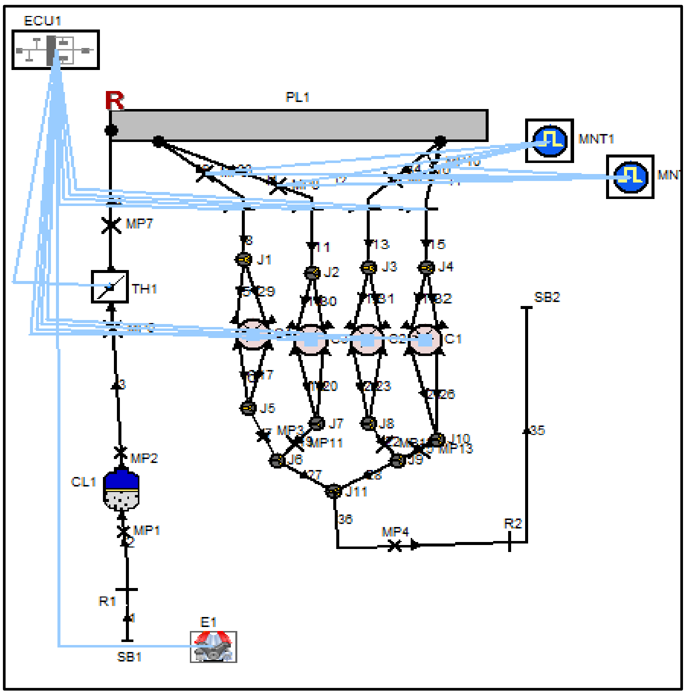


Figure 1: Complete engine simulation on *AVL Boost* software

3.0 RESULTS AND DISCUSSIONS

The collected data from DOE has been analyzed by using the *Design Expert* software. Related analysis such as *ANOVA* analysis, mathematical model equation, normal probability plot, 3D surface graph, contour plot, residual plots and response optimization has been obtained. Two responses were analyzed related to the engine performance and fuel consumption.

3.1 Experimental Matrix Design

Results for the fuel consumption and engine performance that were run through the simulation of 1D CFD are shown in Table 3. The results were obtained by referring to the DOE that has been modeled using the*Design Expert* software. A total of 29 runs each give out two responses that need to be analyzed in order to get an optimized value for the selected geometry of the intake manifold (*A*, *B*, *C* and *D*). This experimental matrix design consists of four factors and five central points as shown in Table 3.

Table 3: Experimental matrix design

Run	**Runner length *A* (mm)**	**Runner diameter *B* (mm)**	**Plenum volume *C* (L)**	**Surface roughness *D* (μm)**	**Fuel consumption ×10^{-4} (kg/s)**	**Engine performance (Nm/rpm)**
1	200.00	34.30	0.50	1.97	8.86	99.2371
2	200.00	34.30	1.80	1.97	9.03	99.9649
3	200.00	34.30	1.15	3.94	8.94	99.4884
4	240.00	20.60	0.50	1.97	8.62	94.2289
5	240.00	34.30	0.50	0.00	8.92	100.253
6	200.00	34.30	1.15	0.00	8.93	99.513
7	240.00	34.30	1.80	0.00	9.12	100.964
8	240.00	34.30	0.50	3.94	8.92	100.235
9	240.00	34.30	1.15	1.97	9.04	100.896
10	200.00	20.60	1.15	1.97	8.75	95.4314
11	280.00	48.00	1.15	1.97	8.98	98.4306
12	240.00	48.00	1.15	3.94	9.01	99.3352
13	240.00	34.30	1.80	3.94	9.12	100.993
14	200.00	48.00	1.15	1.97	9.05	100.088
15	240.00	48.00	1.15	0.00	9.01	99.3381
16	240.00	48.00	1.80	1.97	9.05	99.3175
17	240.00	34.30	1.15	1.97	9.04	100.896
18	280.00	34.30	1.15	3.94	9.08	101.155
19	240.00	34.30	1.15	1.97	9.04	100.896
20	280.00	34.30	1.80	1.97	9.15	101.284
21	280.00	34.30	1.15	0.00	9.08	101.153
22	240.00	34.30	1.15	1.97	9.04	100.896
23	240.00	48.00	0.50	1.97	8.94	99.2503
24	240.00	20.60	1.80	1.97	8.88	95.7842
25	280.00	20.60	1.15	1.97	8.78	94.9467
26	240.00	20.60	1.15	3.94	8.76	95.0965
27	240.00	34.30	1.15	1.97	9.04	100.896
28	280.00	34.30	0.50	1.97	9.00	101.123
29	240.00	20.60	1.15	0.00	8.77	95.272

3.2 Engine Performance

In Table 4, the model *F*-value of 127.65 implies the model is significant. The value of *Prob>F* less than 0.5 indicates the model terms are significant. In this case, *A*, *B*, *C* and *B2* are the significant model terms. The values for *R-Squared* and *Adj R-Squared* are 0.9641 and 0.9566, respectivelyas shown in Table 5. Both values are quite high but deemed reasonable, indicating that the model is indeed significant.

Table 4: ANOVA analysis for the engine performance

Source	**Sum of squares**	**DF**	**Mean square**	***F*-value**	***Prob>F***	
Model	122.13	4	30.53	127.65	< 0.0001	significant
A	2.62	1	2.62	10.97	0.0037	
B	41.26	1	41.26	172.49	< 0.0001	
C	1.32	1	1.32	5.52	0.0298	

B2	68.21	1	68.21	285.15	< 0.0001
Residual	4.54	19	0.24		
Cor total	126.67	23			

Table 5: Regression table for the engine performance

Std Dev	0.49	*R-Squared*	0.9641
Mean	98.86	*Adj R-Squared*	0.9566
CV	0.49	*Pred R-Squared*	0.9377
PRESS	7.90	*Adeq Precision*	29.890

The engine performance in terms of the coded and actual factorscan be expressed as follows:

For the coded factors:

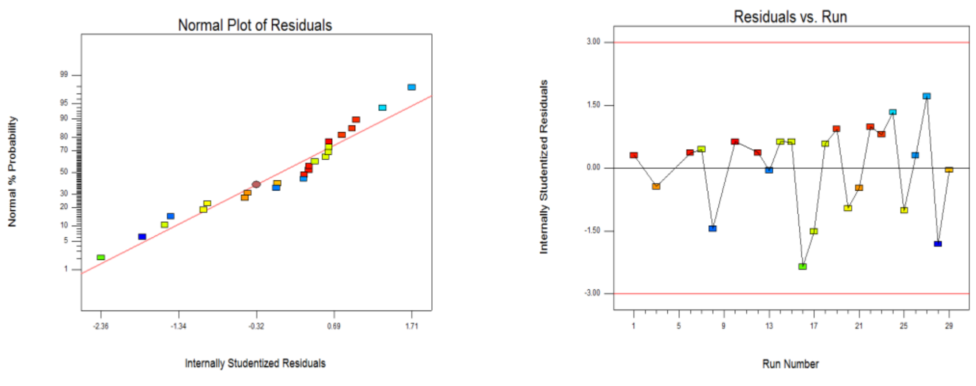
$$Engine\ performance = 100.48 + 0.49A + 1.95B + 0.33C - 3.40B^2 \tag{3}$$

Where A is the runner length, $B$is the runner diameter and $C$is the plenum volume.

For the actual factors:

$$Engine\ performance = 71.31663 + 0.012322\text{A} + 1.38547B - 0.51029C - 0.018117B^2 \tag{4}$$

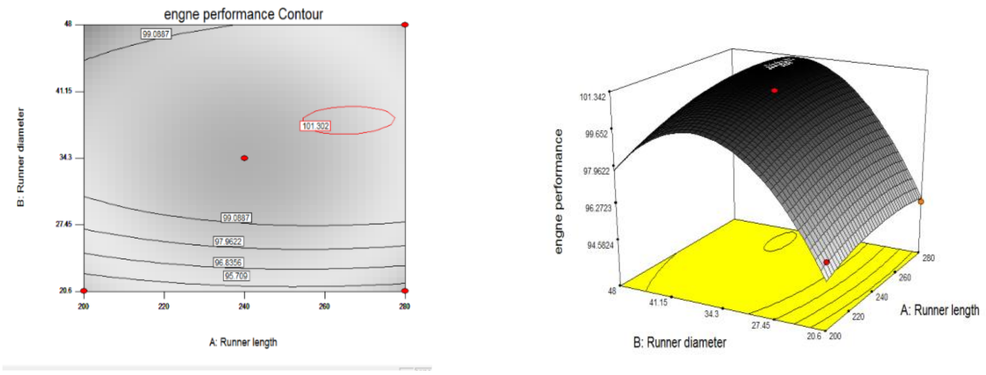
In order to verifythe model, an analysis was performed with reference to Figure 2 that shows the normal plot of residual and residuals vs run graphs. Both graphs show acceptable results;in normal plot, the points should be distributed normally along the straight line as presented and for the residual vs run plot, the data should be randomly scattered.



(a) (b)

Figure 2: Adequacy check for (a) normal plot of residual graph and (b) residual vs run graph for the engine performance

The optimum parameters value is at the peak of the curve as shown in Figure 3. On the contour plot of Figure 3a, the red oval marks the location of the optimum value. In other words, the optimized value is located inside the red oval mark as presented.



(a) (b)

Figure 3: (a) Contour plot and (b) 3D surface graph for the engine performance

3.3 Fuel Consumption

Table 6 shows the ANOVA analysis for fuel consumption considering various models while Table 7 presents the regression table for the fuel consumption. The model *F*-value of 74.49 in Table 6 implies that the model is significant while the value of *Prob>F* less than 0.5 indicatesthat the model terms are also deemed significant. In this case, *A, B, C* and *B2* are the significant model terms. The values for *R-Squared* and *Adj R-Squared* are 0.9586 and 0.9498, respectively as depicted in Table 7. Both values are quite high but reasonable, implying that the model is indeed significant.

Table 6: ANOVA analysis for the fuel consumption

Source	Sum of squares	DF	Mean square	*F*-value	*Prob>F*	
Model	0.41	4	0.10	74.49	< 0.0001	significant
A	0.022	1	0.022	15.72	0.0008	
B	0.18	1	0.18	132.40	< 0.0001	
C	0.099	1	0.099	71.82	< 0.0001	
B2	0.11	1	0.11	78.01	< 0.0001	
Residual	0.028	20	1.379E-003			
Cor total	0.44	24				

Table 7: Regression table for thr fuel consumption

Std Dev	0.031	*R-Squared*	0.9586
Mean	8.95	*Adj R-Squared*	0.9498
CV	0.34	*Pred R-Squared*	0.9277
PRESS	0.031	*Adeq Precision*	35.003

Similar to the previous case, the mathematical models for the fuel consumption are as follows:

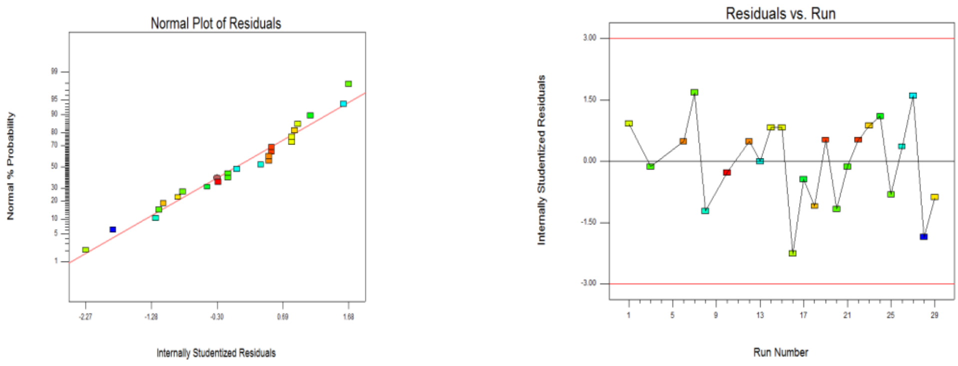
For the coded factors:

$$Fuel\ consumption = 9.01 + 0.052A + 0.12B - 0.091C - 0.14B^2 \quad (5)$$

For the actual factors:

$$Fuel\ consumption = 7.37409 + (1.30093 \times 10^{-3})A + 0.059775B - 0.13974C - (7.50275 \times 10^{-4})B^2 \quad (6)$$

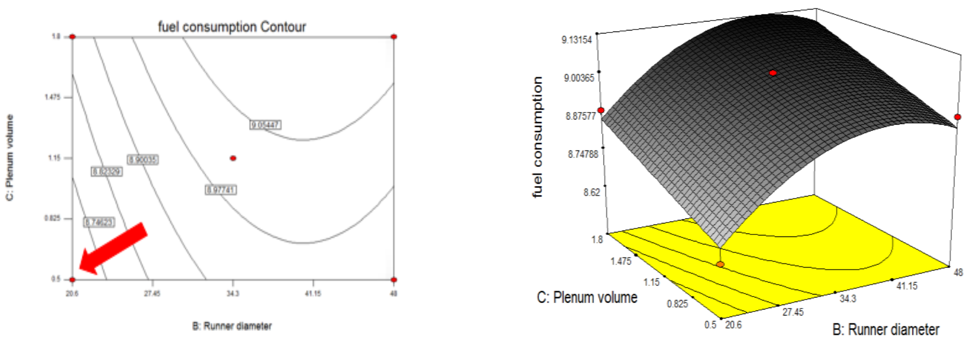
In order to verify the model, an analysis was performed with reference to Figure 4 showing the normal plot of the *Residual* graph and the *Residual* vs *Run* graph. Both graphs show an acceptable result; in the normal plot, the points should be distributed normally along the straight line as shownwhile for the *Residual* vs *Run* plot, the data should be randomly scattered.



(a) (b)

Figure 4: Adequacy check (a) normal plot of residual graph and (b) residuals vs run graph for fuel consumption

In Figure 5, the graph fails to show the center peak.However, it is desirable to find the lowest possible value for the fuel consumption. As can be seen from the contour plot of Figure 5a, the graph tends to show a series bendsat the bottom left of the graph. The fuel consumption decreases when both diametersof the runner and runner lengthwere decreased. A steepest decent method was applied to determine the lowest possible optimized value for the fuel consumption.



(a) (b)

Figure 5: (a) Contour plot and (b) 3D surface graph for the fuel consumption

Data were presented for 10 solutions and all of them were simulated in *AVL Boost* software to determine the fuel consumption. In order to run the simulation, the runner length (*A*) and surface roughness (*D*) were set to a standard range. With reference to previous research, 0.24L was the lowest value studied for plenum volume of intake manifold [8]. The data collected for steepest decent will not include the values less than 0.242L which had been highlighted with red colour in Table 8.

Table 8: Steepest descent results

	Runner diameter (mm)	Plenum volume (L)	Fuel vonsumption (kg/s)×10^{-4}
SR	20.600	0.500	8.03
1	19.558	0.457	7.66
2	18.517	0.414	7.22
3	17.476	0.371	6.74
4	16.435	0.328	6.23
5	15.394	0.285	5.68
6	14.352	0.242	5.14
7	13.311	0.199	4.63
8	12.270	0.156	4.16
9	11.229	0.113	3.77
10	10.188	0.070	3.38

A total of 10 experiments were producedwith reference to the levels and factors as shown in Table 9. The experimental matrix design for steepest descent consisting of two factors including two central pointsis presented in Table 10.

Table 9: Levels and factors for steepest descent

Parameter	Code	Low level (-1)	Central point (0)	High level (+1)
Runner diameter (mm)	*B*	14.35	15.39	16.44
Plenum volume (L)	*C*	0.24	0.29	0.33

Table 10: Experimental matrix design for steepest descent

Run	Runner diameter (mm)	Plenum volume (L)	Fuel consumption (kg/s)×10^{-4}
1	15.40	0.29	5.68
2	15.40	0.29	5.68
3	15.40	0.35	5.68
4	16.44	0.24	6.22
5	15.40	0.22	5.67
6	14.35	0.33	5.14
7	16.87	0.29	6.44
8	14.35	0.24	5.14
9	13.92	0.29	4.94
10	16.44	0.33	6.23

Table 11 presents the ANOVA analysis for the steepest descent method while Table 12 shows the regression table for steepest descent.

Table 11: ANOVA analysis for the steepest descent

Source	Sum of squares	DF	Mean square	*F*-value	*Prob>F*	
Model	2.29	2	1.14	609.54	< 0.0001	significant

A	2.29	1	2.29	1219.05	< 0.0001
B	7.019E-005	1	7.019E-005	0.037	0.8522
Residual	0.013	7	1.878E-003		
Lack of fit	0.013	6	2.191E-005		
Pure error	0.000	1	0.000		
Cor total	2.30	9			

Table 12: Regression table for steepest descent

Std Dev	8.931E-003	*R-Squared*	0.9998
Mean	5.68	*Adj R-Squared*	0.9997
CV	0.16	*Pred R-Squared*	0.9994
PRESS	1.312E-3	*Adeq Precision*	310.154

In Table 11, the model *F*-value of 609.54 implies that the model is significant. A value of *Prob>F* less than 0.5 indicatesthat the model terms are significant. In this case, only *A* is the significant model term. The values for *R-Squared* and *Adj R-Squared* are 0.9998 and 0.9997, respectively as shown in Table 12. Both values are quite high, thereby indicating that the model is significant. Thefuel consumptioncan be expressed as:

For the coded factors:

$$Fuel\ consumption = 5.68 + 0.58\mathrm{A} + (3.206 \times 10^{-3})\mathrm{B} \quad (7)$$

For the actual factors:

$$Fuel\ consumption = -2.86849 + 0.55409\mathrm{B} + 0.071245\mathrm{C} \quad (8)$$

3.4 Maximum Engine Performance and Minimum Fuel Consumption

The optimized parameters for the maximum engine performance and minimum fuel consumption had been obtainedas: *A* = 200.00mm, *B* = 35.56mm, *C* = 0.5L and *D* = 0.15µm. The engine performance and fuel consumption were found to be 99.5410 Nm/rpm and 8.8652 × 10^{-4}, respectively.

3.5 Confirmation Run

The percentage of error for each confirmation runs shows a value less than 1% as depicted in Table 13. This proves that the engine simulation in this study is accurate and reliable because the actual value is closed to the predicted value. Thus, the differences between the two values are too small.

Table 13: Confirmation run for maximum engine performance and minimum fuel consumption

No.	Runner length (mm)	Runner diameter (mm)	Plenum volume (L)	Surface roughness (µm)	Engine performance (Nm)		Fuel consumption (kg/s)×10^{-4}		Error (%)	
					Predicted	Actual	Predicted	Actual	Eng.perform.	Fuel consump.
1	200.000	33.560	0.500	0.150	99.54	99.74	8.87	8.88	0.19	0.22
2	200.001	32.770	0.559	3.939	99.43	99.77	8.87	8.89	0.34	0.28
3	222.487	43.926	0.500	0.000	99.63	99.85	8.9	8.95	0.22	0.45
4	240.985	30.818	0.500	0.257	99.45	99.72	8.89	8.90	0.27	0.1
5	260.416	29.412	0.500	3.940	99.27	99.60	8.892	8.90	0.33	0.14

3.6 Proposed Model of the Optimized Intake Manifold

A 3D model of the proposed model for the optimized intake manifold can be seen in Figure 6 based on the results obtained in this study. The optimized value for the surface roughness was selected as the reference value for the selection of the material and manufacturing process in the development of the intake manifold. The material and manufacturing process deemed most suitable for the product are polyamide and injection molding.

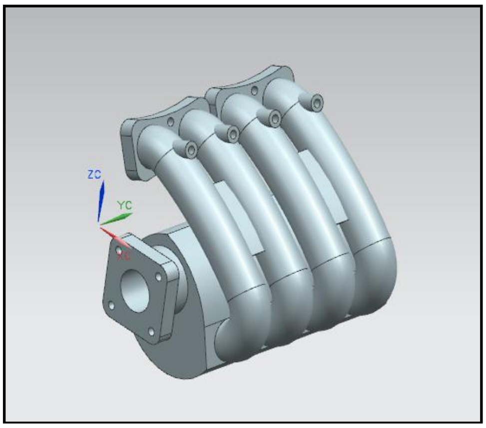


Figure 6: Model of the optimized intake manifold

4.0 CONCLUSION

The engine simulation has been designed and implemented using *AVL Boost* software to obtain the essential parameters or responses for this study, namely, the engine performance and fuel consumption. The parameters involve has been determine so the study will focus more on the selected parameters which are runner length (*A*), runner diameter (*B*), plenum volume (*C*) and surface roughness (*D*). These parameters were defined to be the main factors in designing the experimental matrix design using*Design Expert* software for the engine system. In the study, the optimized parameters were obtained as: A = 200.00mm, B = 35.56mm, C = 0.5L and D = 0.15μm. The optimization of the engine based on these optimized parameters produces the maximum engine performance and minimum fuel consumption that were found to be 99.5410 Nm/rpm and 8.8652×10^{-4} kg/s, respectively. Moreover, the optimized intake manifold based on the results has been modeled in CAD software (*NX8.0*). Last but not least, the selection of material and the manufacturing process for the optimized intake manifold were also determinedusing polyamide and injection molding, respectively. The successful of this study is attributed to the new design of the intake manifold which can enhance the engine performance and at the same time has a good fuel economy.

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