DEVELOPMENT AND MATERIAL OPTIMIZATION OF 0.67HP PETROL GENERATOR CYLINDER BLOCK USING TAGUCHI DESIGN AND FINITE ELEMENT ANALYSIS

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ABSTRACT

The development of 0.67Hp gasoline generator cylinder block and the material optimization of the component using Taguchi Design and Finite Element Method were carried out successfully. The cylinder block is known to create an avenue for the piston to carry out its reciprocating effect on the crankshaft for onward transmission for the machine output. The designed cylinder block had an engine power of 5.11kw which drove piston through a bore and stroke length of 46.10mm and 51.20mm respectively. The determined clearance volume of 9.46cm^3 was contained in a cylinder wall thickness and block length of 3.04mm and 58.88mm respectively. The designed values were found to be in consonance with recommended values obtained in standard engineering text. The developed mathematical model was determined to be adequate with a statistical Coefficient of determination (R^2) of 98.62% and the Adjusted coefficient of determination (Adj R^2) was found to be 97.79%. The comparison of optimal values developed from the Taguchi design and genetic algorithm optimizations showed that obtained values from both methods were noticed to be very close as only a difference of about 0.0005 existed among the input parameters. The genetic algorithm result was seen as a kind of validation for the Taguchi design optimization. The Finite element analysis result showed that the temperature output result recorded the highest temperature of 100^{o}C around the cylinderical bore axis while the lowest temperature of 51.97^{o}C was found on the cooling fins of the component.

Keywords: Optimization, Taguchi Design, Genetic Algorithm and Finite Element Analysis.

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1. Introduction

Cylinder block is the foundation on which every other components of the internal combustion engine is situated. The internal combustion engine is a heat engine that converts the chemical energy inherent in a gasoline and diesel fuel to a rotational mechanical energy delivered to crankshaft to develop the requisite output of the machine (Aliemeke and Oladeinde, 2020). The internal combustion engine components such as crankshaft, pistons, sleeves and connecting rods are all fixed in various designed compartments of the cylinder block (Kaisan and Pam, 2013). The cylinder block is known to create an avenue for the piston to carry out its reciprocating effect on the crankshaft for onward transmission for the machine output (Amalu and Ibhadode, 2007). It important to note that the component is the strongest and largest part of the engine as it consist of over 35% of the total weight internal combustion engine and as such it is made up of a material reputed to be of high strength since it serve as structural support for engine (Ebhojiaye and Sadjere, 2017). This attest to the fact of the constant use of materials that are ferrous based alloys in the production of cylinder blocks in various automobiles and generators (Joshhi, 2019).

In the development of the cylinder block, it is pertinent that some of the component parameters such as stroke length, cylinder bore, indicated power, mechanical efficiency, compression ratio and engine torque are designed for to have adequate and feasible operating values for block (Ebhojiaye and Sadjere,2017). This present dispensation has made it possible for components to be designed in Computer Aided Design (CAD) interface to ascertain its favourable and operating conditions. Designed graphical models from the 3D CAD interface are imported into the Finite element environment for simple simulations that can lead to the prediction of mechanical, thermal and performance parameters (Carvelheira and Goncalves, 2006). The Finite Element Method also creates the opportunity for determining the operating conditions of components by applying some suitable boundary conditions. This is made possible by its ability to divide the structural component into miniaturized segments for ease of computation (Venkatareddy and Goud, 2016). This create a lot of critical examination on components on the computer before been deployed for outright production. This will help reduce lead time for production and ascertain behavioural pattern of the components.

The best practices of production of components in this fast emerging technology is obtained by the optimization of material parameters and processes. Optimization tools such as Taguchi method, Response Surface Methodology (RSM) and Finite Element Method has began to take foundational roots as they to ensure simple efficient means of optimizing systems, processes and design parameters in order to increase performance characteristics and reduce cost (Patel,Krishna,Vundavilli and Parappagouder,2016). A lot of work has been done with the Taguchi Method through the application of Design of Experiment approach in determining the optimal conditions for design parameters and processes (Nekere, and Singh,2012). It recommends orthogonal arrays for the conduct of experiments.

This study is targeted towards the development of a 0.67Hp gasoline generator cylinder block and the material optimization of the component using Taguchi Design and Finite Element Method.

2. Methodology

The important parameters of the 0.67Hp cylinder block such as bore diameter, stroke length, mechanical efficiency, clearance volume and engine torque were determined. Also Taguchi design and Genetic algorithm was applied in the parametric optimization. Finite element analysis was targeted towards thermal optimization of the internal combustion component.

2.1 Design of the 0.67Hp Cylinder block

In designing for the cylinder block, data for internal combustion engines as shown in Table 1 was utilized and some specifications were made with the guidance of some standard engineering texts. The design considerations made were:

a. Mechanical Efficiency of 75%
b. Speed of engine was 3000rpm

c. Mean brake efficiency pressure of 360Mpa
d. Swept volume of $85cm^3$.
e. Bore diameter to piston stroke of 0.8:1.2
f. 2- stroke engine

Table 1: Data for Internal Combustion engines (Aliemeke and Oladeinde, 2020)

Engine Type	Operating Cycle	Compression Ratio	Bore (m)	Rated Maximum					
				Stroke/ bore	Speed, (rpm)	Bmep, (atm)	Power/ unit volume, kW/dm^3	Weight/ Power ratio, kg/kW	Approx. Best bsfc, g/kW.h
Spark-ignition Engines:									
Small (e.g., Motorcycles)	2S, 4S	6 - 11	0.05-0.085	1.2– 0.9	4500-7500	4 - 10	20 – 60	5.5– 2.5	350
Passenger Car	4S	8 – 10	0.07 – 0.1	1.1– 0.9	4500-6500	7 - 10	20 – 50	4– 2	270
Trucks	4S	7 – 9	0.09 – 0.13	1.2– 0.7	3600-5000	6.5 - 7	25 – 30	6.5– 2.5	300
Large Gas Engines	2S, 4S	8 – 12	0.22 – 0.45	1.1– 1.4	300-900	6.8 - 12	3 – 7	23– 35	200
Wankel Engines	4S	≈ 9	$0.57 dm^3$ /chamber		6000-8000	9.5 – 10.5	35 – 45	1.6– 0.9	300

2.1.1 Determination of the bore diameter of the cylinder block

The bore diameter of the 0.67Hp generator cylinder block was determined by applying equation (1) obtained from Sharma and Aggarwal(2013)

$$S_v = \frac{\pi n B_d^2 S_p}{4} \quad (1)$$

Where S_v=Swept volume

B_d=Bore diameter

S_p=Stroke length

n=number of cylinders

With recourse to Table 1 the ratio of bore diameter to the stroke length, S_p is taken to be 0.9. That simply means that the bore diameter is 0.9Sp. Substituting for swept volume and speed in equation (1) gave rise to equation (2) obtained from Pulkrabek(2003).

$$85 = \frac{\pi \times 1 \times 0.9Sp^2 \times Sp}{4} \quad (2)$$

The stroke length was determined to be 51.20mm consequent upon the bored diameter was calculated to be 46.10mm.

2.1.2 Determination of the 0.67Hp engine torque

The torque which is one of the key engine performance parameters was determined by the application of equation (3) obtained from Khurmi and Gupta(2008)

$$T_q = \frac{M_p \times S_v}{2\pi \times r_n} \quad (3)$$

Where T_q =Engine torque in Nm

r_n= number of revolution

M_p=Mean effective pressure in Kpa

The mean brake pressure for spark ignition engines is maximum at 1050Kpa for engine speed of 3000rpm. A mean pressure of 900Kpa was used in this study. By substitution of swept volume, mean effective pressure and the number of revolution into equation (3) yielded an engine torque of 12.177Nm.

2.1.3 Determination of engine indicated power

Firstly, the brake power generated by the engine cylinder block of the 0.67Hp generator was determined by the application of equation (4) obtained from Khurmi and Gupta(2014).

$$P_b = \frac{2\pi T_q N}{60} \quad (4)$$

Where P_b=brake power

N= speed in rpm

The brake power was determined to be 3.83Kw for a speed of 3000rpm.

The determined brake power was substituted into equation (5) which was used for the calculation of the indicated power.

$$\ell_m = \frac{P_b}{P_i} \quad (5)$$

Where ℓm=Mechanical efficiency

Pi =indicated power

The indicated power was calculated to be 5.11Kw from a mechanical efficiency of 75%.

2.1.4 Determination of cylinder wall thickness

The wall thickness of the cylinder was determined by the use of equation (6) obtained from Heywood (1988).

$$T_w = \frac{P_g \times B_d}{2\delta_s} + R_f \quad (6)$$

Where T_w=Wall thickness in mm

P_g=maximum pressure on the gas

R_f=reboring factor

δ_s= Circumferential stress in N/mm^2

The wall thickness was calculated to be 3.04mm for a maximum gas pressure, circumferential stress and a reboring factor of 3.6N/mm^2, 51N/mm^2 and 1.5 respectively.

2.1.5 Determination of the length of the cylinder block

The length of the component is known to be longer than the piston stroke consequent upon a 15% of the stroke length is passed for the clearance of the cylinder block. And as such the cylinder block is determined using equation (7) obtained from Pulkrabek(2003).

$$L_c = S_p + 15\%S_p \quad (7)$$

Where L_c=length of cylinder block

The cylinder length was determined to be 58.88mm for a piston stroke of 51.20mm.

2.1.6 Determination of Clearance volume

The clearance volume of the cylinder block was determined by using equation (8) obtained from Ebhojiaye and Sadjere(2017).

$$c_r = \frac{S_v + C_v}{C_v} \quad (8)$$

Where C_v=clearance volume

C_r= compression ratio

The compression ratio was taken to be 10 as Table 1 has it to be between 6-11for small spark ignition engines. Substituting the values of compression ratio and swept volume into equation (8) yielded a clearance volume of 9.46cm^3.

2.2 Taguchi Design Method

The Taguchi design is an optimization tool for determining the best conditions for manufacture of products. It is the simplest way of optimizing machine or process parameters of an experiment by prescribing lower number experimental trials when compared to Full-factorial and Response Surface Methodology (Oji,Sunday and Adetunji,2013). The robust method is noticed to be economical as it performs less number of experiments which translates into less time consumption (Nekere and Singh, 2012). The number of factors and levels determine the number of experimental runs that can be observed. The Taguchi method deploys the Signal-to-Noise ratio technique in determining the performance characteristics of the response parameter in terms of the input parameters. The Signal-to-Noise ratio entails: Lower-the better, Nominal-the better and Larger-the better (Mohiuddin, Krishnaiah and Hussainy, 2015).

2.2.1 Design of Experiment (DOE)

The Design of experiment is a platform designed to carry out experiments at various conditions with a view of determining the best conditions suitable for optimum production. It is a planned statistical technique for examining and varying the influence of several input parameters simultaneously (Patel et al, 2016). The platform employs the Orthogonal Arrays in the display of the conditions for experimentation. In this study 3 input parameters and 3 levels were employed. Table 1 shows the input parameters and their levels. The parametric ranges used in Table 1 were arrived at after profound study of some related literature (Prajapati and Patel, 2017)

Table 1: Input parameters and their levels

Input parameter	Level 1	Level 2	Level 3
Injection pressure(Mpa)	20	18	16
Load(N)	1	5	9
Compression ratio	12	10	8

The Taguchi L_9 orthogonal array was employed in this study to accommodate the conditions required for 3 factors and 3 levels. A total of nine experimental runs shown in Table 2 were prescribed by the Minitab 18 software

Table 2: Design of Experiment Conditions

	Injection pressure(Mpa)	Load(N)	Compression ratio
1	20	1	12
2	20	5	10
3	20	9	8
4	18	1	10
5	18	5	8
6	18	9	12
7	16	1	8
8	16	5	12
9	16	9	10

2.3 Experimental Set-up

An engine test bed shown in Figure 1 was used for the experimentation. The 0.67Hp generator engine having the single cylinder block was placed in a tilting arrangement close to the test bed. The compression ratio was changed at a given interval of time. The various measurement devices were made to interface with the air and fuel flow, air pressure and load.

Figure 1: Engine Test bed for experimentation

2.4 Multiple Linear Regression

The Multiple linear regression technique was employed in the development of mathematical models for the response parameter. It became imperative to apply this statistical model since we had three input parametric values in this study. The Least Square method was used in estimating the regression coefficients in the developed Mathematical model.

2.5 Genetic Algorithm

The Genetic algorithm was coneptualised on the application of biological processes to the way and manner in which living organisms engage in survival of the fittest test within the population in successive generations. The evolutionary Genetic Algorithm was used to predict optimal values for the developed mathematical models. The algorithm utilized evolution biological processes such as mutation, cross over, chromosome selection and reproduction in determining the fitness value of objective function (Azhagan, Mohan and Rajadurai, 2014). In carrying out the optimization process, the developed mathematical model was introduced into the algorithm tool box for as an objective function.

3. Results and Discussion

The results obtained from the development of the 0.67Hp gasoline generator cylinder block, Test rig experimentation data, mathematical and graphical model development, Taguchi Design, Genetic algorithm optimization and Finite element thermal optimization are presented in this section

3.1 Summary of the Designed values

The summary of the designed values for the 0.67Hp Cylinder block of 0.67Hp generator are presented in Table 3. The designed values were found to be in consonance with recommended values obtained in standard engineering text. Furthermore, the calculated values were found to be similar to that obtained in Ebhojiaye and Sadjere (2017) and Aliemeke and Oladeinde (2020)

Table 3: Summary of the Designed values

S/N	Parameter	Designed value
1	Cylinder block diameter	46.10mm
2	Piston stroke	51.20mm
3	Engine Torque	12.177Nm
4	Indicated Power	5.11Kw
5	Brake Power	3.83Kw
6	Cylinder wall thickness	3.04mm
7	Cylinder block length	58.88mm
8	Clearance volume	9.46cm^3

3.2 Graphical Modelling of the Cylinder Block

The isometric drawing and Third Angle orthographic projection of the cylinder block which were drawn using AutoCAD 16 software are shown in Figures 2 and 3 respectively.

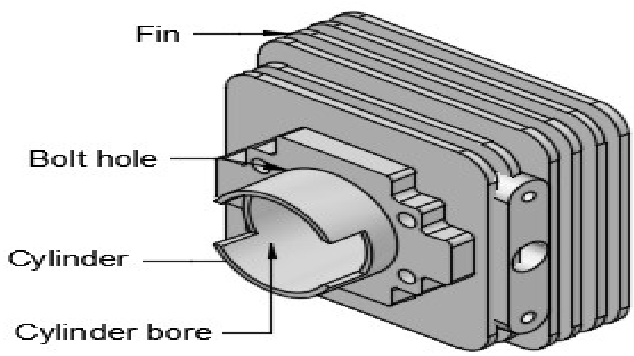

Figure 2: Isometric Drawing of the Cylinder block

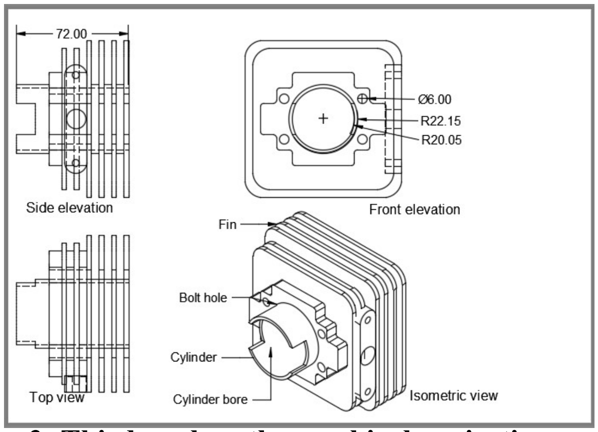

Figure 3: Third angle orthographical projection

3.3 Taguchi design Analysis

The result obtained from the experimentation of the cylinder block on the engine test bed is shown on Table 4.

Table 4: Experimentation for Response Parameter (SFC)

	A	B	C	Y
1	20	1	12	0.75
2	20	5	10	0.90
3	20	9	8	0.96
4	18	1	10	0.89
5	18	5	8	0.98
6	18	9	12	1.20
7	16	1	8	0.99
8	16	5	12	1.25
9	16	9	10	1.28

The developed mathematical model from the application of the multiple linear regression technique is shown in eqation (9)

$$Y = 1.993 - 0.07583A + 0.03375B + 0.0225C \quad (9)$$

Where Y=Specific Fuel Consumption (SFC) in kg/kwh

A=injection pressure in Mpa

B=Load in N

C= consumption ratio

The optimal levels of the input parameters obtained from the Taguchi Design and Signal-to-noise are shown on Table 5 and Figure 4 respectively. The predicted value for the response parameter (Specific fuel consumption) is 0.680 kg/Kwh.

Table 5: Optimal levels from Taguchi Design

Input parameter	Lower bound	Upper bound	Optimal level
Injection pressure(Mpa)	16	20	20
Load(N)	1	9	1
Compression ratio	8	12	8
Specific fuel consumption(kg/Kwh)			0.680

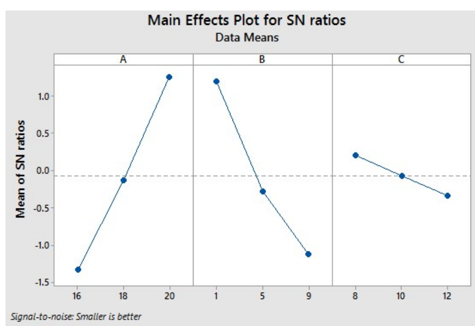

Figure 4: Signal-to-noise ratio plot

The developed mathematical model was found to be statistically adequate with a p-value lesser than 0.05 using a significant level of 0.05. Also, the 3 input parameters were found to be significant as a result of them having a p-value that is less than 0.05 as shown on Table 6.

Table 6: ANOVA result

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	0.259517	0.086506	118.86	0.000
A	1	0.138017	0.138017	189.64	0.000
B	1	0.109350	0.109350	150.25	0.000
C	1	0.012150	0.012150	16.69	0.009
Error	5	0.003639	0.000728		
Total	8	0.263156			

3.4 Further Test on Model adequacy

The developed mathematical model was further subjected to the statistical Coefficient of determination (R^2) test which yielded 98.62% and the Adjusted coefficient of determination (Adj R^2) was found to be 97.79% which showed a high level of model adequacy. In order to give credence to the adequacy of the model a probability plot was developed for the set data. The developed Normal probability plot shown in Figure 5 indicates that the data are distributed around the diagonal line which portrays a great sign of model adequacy.

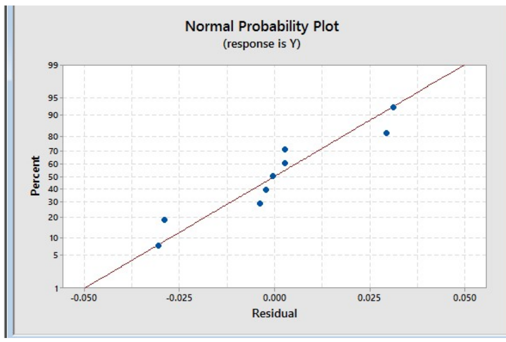

Figure 5: Normal probability plot for Specific fuel consumption

3.5 Genetic algorithm result

The developed mathematical model was inputted into the Matlab genetic algorithm tool box. A generation of 100 was searched for using the heuristic and roulette wheel approach for crossover and selection respectively. The optimal levels obtained from genetic algorithm are shown on Table 7.The result for best fitness and individual of the first 100 generations are shown in Figure 6.

Table 7: Optimal levels from Genetic algorithm

Input parameter	Lower bound	Upper bound	Optimal level
Injection pressure(Mpa)	16	20	19.9995
Load(N)	1	9	1.0005
Compression ratio	8	12	8.00061
Specific fuel consumption(kg/Kwh)			0.6904

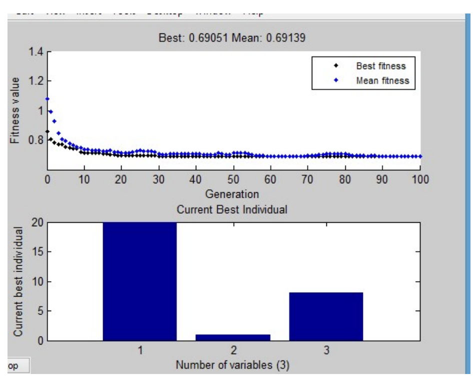

Figure 6: Best fitness for 100 generations

3.6 Comparison of Taguchi and genetic algorithm results

The optimal values developed from the Taguchi design and genetic algorithm optimizations were compared as shown in Table 7. The obtained values from both methods were noticed to be very close as only a difference of about 0.0005 existed among the input parameters. The genetic algorithm result was seen as a kind of validation for the Taguchi design optimization. The obtained optimal values were similar to that in Prajapati and Patel(2017).

Table 7.0: Comparison of Taguchi and Genetic Algorithm results

Input parameter	Taguchi	Genetic Algorithm	Difference
Injection pressure(Mpa)	20	19.9995	0.0005
Load(N)	1	1.0005	0.0005
Compression ratio	8	8.0006	0.0006
Specific fuel consumption(kg/Kwh)	0.6801	0.6904	0.0103

3.7 Finite Element Analysis

The developed cylinder block was subjected to Finite element analysis to ascertain the optimal values of the thermal condition of the component. The AutoCAD designed internal combustion engine component was imported into the Steady state thermal analysis environment of the Finite element ANSYS software. The component was meshed into 10190 and 19616 elements and nodes respectively as shown in Figure 7.

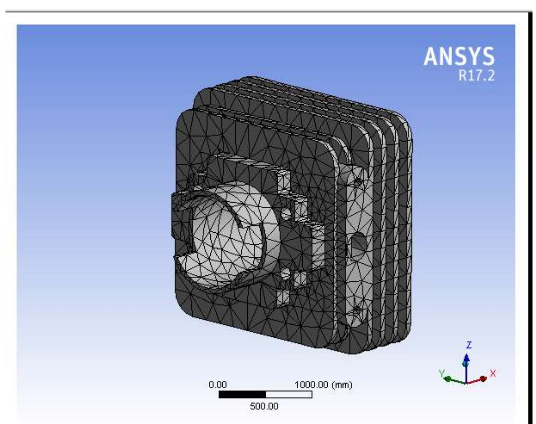

Figure 7: Meshed Cylinder block

The already meshed component had its cylindrical compartment inputted with a temperature of 100ºC as shown in Figure 8. Also, a stagnant-air horizontal at 22ºC was used as the convection value for the entire cylinder block as shown in Figure 9.

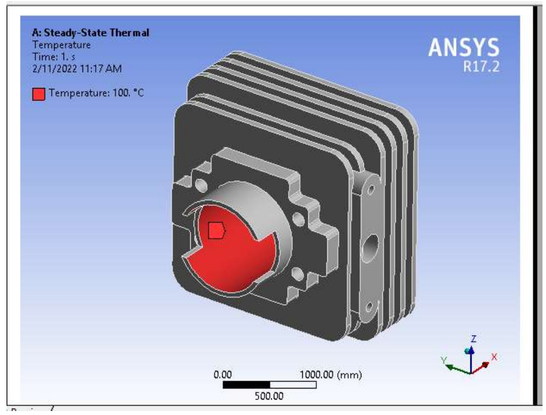

Figure 8: Temperature inputted cylinder block

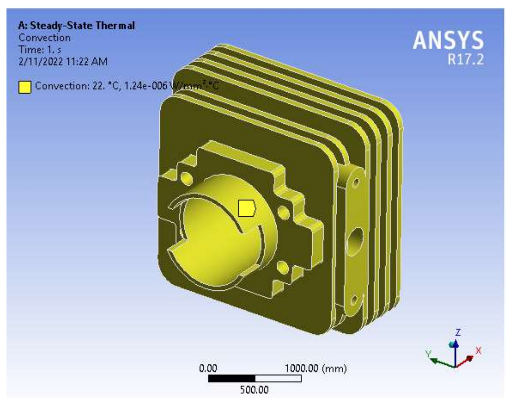

Figure 9: Convection Enclosed block

The cylinder block was further subjected to temperature and total heat flux output analysis in order to ascertain the effect of the inputted parameters on the component as shown on Figures 10 and 11 respectively. The temperature output result showed that the highest temperature of 100°C occurred around the cylinderical bore axis while the lowest temperature of 51.97°C was found on the cooling fins of the component . Similarly, the total heat flux had its maximum value around the cylindrical bore and its minimum on the cooling fins. The outputs were found to be similar to the values obtained in Vengatesvaran,Prithiviraj and Periyasamy (2018).

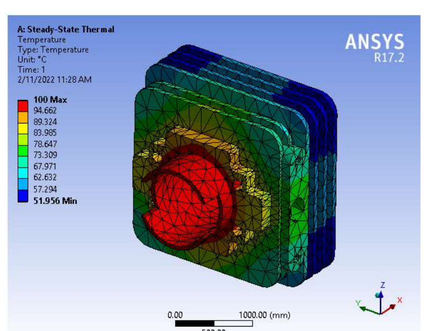

Figure 10: Cylinder Block Temperature output

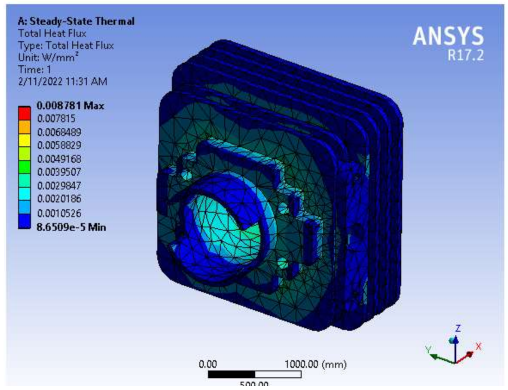

Figure 11: Cylinder block convection output

Furthermore, it was shown on Figure 12 that increase on temperature of the component leads to an increase of convection.

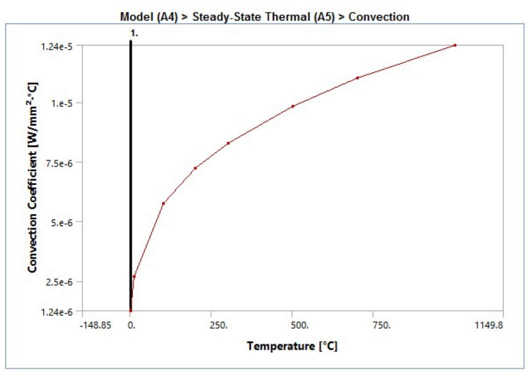

Figure 12: Convection versus Temperature graph

4. CONCLUSION

The designed cylinder block had an engine power of 5.11kw which drove piston through a bore and stroke of 46.10mm and 51.20mm respectively. The determined clearance volume of 9.46cm^3 was enclosed in a cylinder wall thickness and block length of 3.04mm and 58.88mm respectively. The designed values were found to be in consonance with recommended values obtained in standard engineering text

The parametric optimization yielded an adequate mathematical model with a statistical Coefficient of determination (R^2) and Adjusted coefficient of determination (Adj R^2) of 98.62% and 97.79% respectively. The Taguchi design and the Genetic algorithm optimization results were found to have optimal values of 19.9995mpa, 1.0001N and 8.0006 for injection pressure, load and compression ratio respectively.

The cylinder block was further subjected to temperature and total heat flux output analysis in the Finite element ANSYS software to ascertain the effect of the inputted parameters on the internal combustion engine component. The temperature output result showed that the highest temperature of 100^{o}C occurred around the cylinderical bore axis while the lowest temperature of 51.97^{o}C was found on the cooling fins of the component.

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