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Taguchi Method for Piston Design and Their Optimization Process

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ABSTRACT

The Taguchi method is used to identify the best settings for diesel engine pistons by optimizing the temperature and stresses created within the coatings using Minitab Software. The current study aims to present a comprehensive literature review on the application of the Taguchi method in various fields of engineering, with a focus on the impact of various operational parameters on multiple performance measures, which can lead to the development of optimal parametric combinations that can improve the process and produce optimized results. These studies found that this optimization strategy was effective in lowering operational costs and streamlining the design process. The major competition between industries in current globalization period is tied to two main aspects: quality and productivity. Productivity is concerned with the company's profitability, which includes increasing production rates while lowering costs and shortening lead times. ANSYS 15 is used to perform a thermal analysis for a high temperature condition. The purpose of this research is to see how piston shape, butanol fumigation, EGR, injection pressure, and injection timing affect the performance and emissions of a light-duty DI diesel engine that runs on diesel, Jatropha methyl ester (JME), and 20% by vol.

II. Introduction

The rising demand for various things in many fields. As the population grows, so does the demand for products and services, which grows in lockstep with the population. Increasing manpower is insufficient to address these issues because the most important prerequisite for producing a big quantity of goods with minimal defects is the optimizationofprocessparameters. For this reason, GenichiTaguchi devised a system for improving the quality of the items produced on his farm, which became known as the Taguchi methods or Taguchi Technique. This technique is no longer limited to the subject of forming; it is now widely employed in fields such as engineering, marketing, biotechnology, advertising, and production. This chapter primarily provides an overview of tribological features that can be used to improve the performance of an IC engine. The study's scope is also stated at the end of this chapter. The internal combustion engine (IC), as depicted schematically in Fig. 1, is the most important mechanical invention made by humans, and it played a significant part in the global industrialization following World War II. However, due to the rapid depletion of traditional fuel resources and rising environmental concerns, researchers around the world are under constant pressure to produce ever more fuel-efficient and compact IC engines

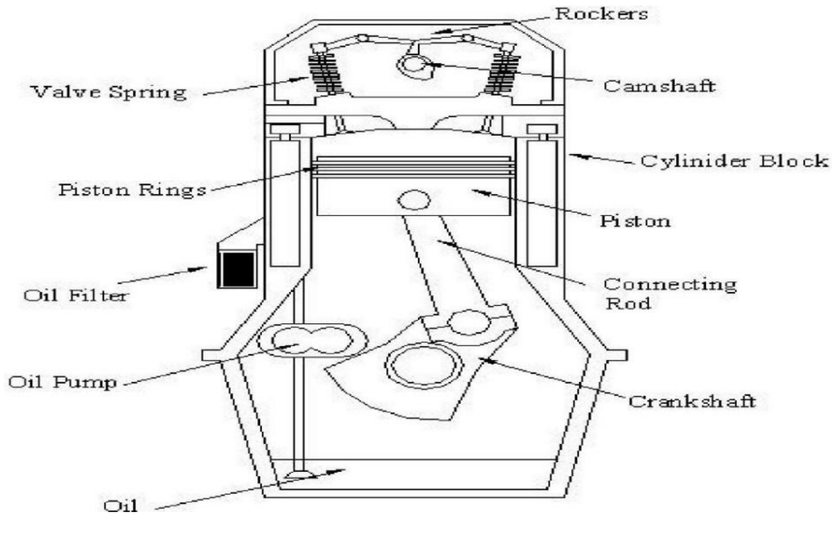

Fig. 1 Vital components of a typical IC engine

with fewer environmental concerns. Many studies on frictional evaluations at various interfaces in IC engines have been conducted in recent decades in order to determine the critical interfaces of the engine components for minimizing the interfacial frictional losses associated with it. Taguchi divides quality into two categories: offline and online. Both of these areas are quite cost-conscious. Offlinequalitycontrol is concerned with the enhancement of product and process development quality. Onlinequalitycontrol is concerned with the monitoring of current manufacturing processes in order to ensure that the quality levels produced are satisfactory. Taguchi technique bared designs differ from traditional experiment designs in that the Taguchi method reduces the variation of interest features. However, it has a significant drawback in that it can only be used to solve single-response situations. It is worth noting that a significant part of fuel energy (i.e. chemical energy) is wasted as heat. Even the frictional resistance present at the numerous interfaces of the moving engine components consumes a large percentage of the chemical energy generated during the burning of valuable fuel. Improved lubrication is significantly responsible for lower fuel consumption and emissions in internal combustion engines. As a result, advanced concepts for reducing friction at various interfaces in an IC engine are now being investigated.

A design strategy's first step is known as concept design. This stage gathers technical information and experiences to assist the designer in selecting the best design for a particular product. Then comes parameter design, when the best control factor setting is determined. This is the most significant phase because it has no bearing on the manufacturing cost of any individual product unit. After you've completed the first two steps, you'll go on to the third step, which is termed tolerance design. Integrated DoE and optimization techniques were used to study the multiple injection strategy, EGR, and intake boost pressure in a DI diesel engine with the goal of reducing NOx and smoke emissions without sacrificing performance. Taguchi divides quality into two categories: offline and online. Both of these areas are quite cost-conscious. Offlinequalitycontrol is concerned with the enhancement of product and process development quality. Onlinequalitycontrol is concerned with the monitoring of current manufacturing processes in order to ensure that the quality levels produced are satisfactory. Taguchi technique bared designs differ from traditional experiment designs in that the Taguchi method reduces the variation of interest features. However, it has a significant drawback in that it can only be used to solve single-response situations. In three steps, the Taguchi technique optimizes a process or product design.

- Concept design or Systemdesign
- Parameterdesign
- Tolerancedesign

A design strategy's first step is known as concept design. This stage gathers technical information and experiences to assist the designer in selecting the best design for a particular product. Then comes parameter design, when the best control factor setting is determined. Despite the fact that many studies have been carried out on reducing NOx and smoke emissions from diesel engines, these studies have been limited to the effects of design or fuel characteristics on engine emissions. Because both elements have an impact on the engine's NOx and smoke emissions, it's important to look into the combined influence of design and fuel parameters on diesel engine emission control.

III. Methodlogy

The Taguchi method is an experimental optimization methodology that determines the amounts of control parameters for experimental trial runs using typical orthogonal arrays. Using this array, we can collect the most information from a small number of experiments while also determining the ideal amount of each parameter. Krishnan et al. investigated the use of light-weight materials like improved ultra-high tensile strength steels, aluminum and magnesium alloys, polymers, and carbon-fiber reinforced composite materials. The piston's lifetime is extended by introducing a new composite matrix of aluminum with silicon carbide particles, which has the most placed on issue and has the same normal performance as Al 6061 alloy in reinforcement with Silicon carbide, with the exception of a minor variation in attributes. Aluminum and silicon carbide in the ratio of 2:3 are used to design and examine the piston. A parametric version of a piston is created in 3-D using the Autodesk Inventor software tool. Sinha et al. used finite element analysis (FEA) software called ANSYS Workbench to numerically analyze the piston's thermomechanical functioning under a prescribed thermal and structural loadload. To improve the engine's overall performance, the piston's weight has been kept to a bare minimum by the employment of fine measurements. The strain has also been kept below a positive limit in this device of optimization, and this system of optimization has been carried out in software called SolidWorks. Thermal barrier coatings (TBC) have been placed on the piston to increase its thermal average performance, and their thermo mechanical performance has been analyzed using couple-subject evaluation in ANSYS. Gopal et al. investigated the mechanics of a 4-wheeler petrol engine's piston, connecting rod, and crank shaft. The assembly should be rigid, and the meeting should move like a mechanism. It was suggested that the meeting's additives be replaced with fresh sets of compounds, and that the parameters be tested using the static, dynamic, and thermal assessment methods. The meeting's most important components, namely the engine piston, connecting rod, and crankshaft, were modelled and constructed according to the supplied design, and the FEA was completed in ANSYS. Hyper Mesh was used to complete the meshing. Shahnaz et al. explore the thermal properties of a piston constructed of cast aluminum alloy and titanium alloy. The main goal is to analyze and investigate the thermal strain distribution of the piston on the real engine state at some point during the combustion process. This work progresses by employing finite element analysis to predict increased pressure and critical location on the side. The ANASYS software tool is used to analyze the piston under thermal loads and mechanical hundreds in order to determine its displacement, thermal, and pressure appropriation. The results show that temperature transfer occurs at the piston's pinnacle factor while the piston is under thermal load, and quality pressure occurs on the piston stick while the piston is under the warmth shape coupling. Pandey et al. examined the design, evaluation, and optimization of a strong and lightweight 4-stroke S.I. engine piston using ANSYS software and finite element analysis. The response surface optimization module is used to optimize the piston. The thickness of the piston barrel is reduced by fifty-two percent, or 28 percent, the thickness of the piston crown head is increased by 9.41 percent, the width of top land is increased by 3.81 percent, the axial thickness of the hoop is increased by 2.38 percent, and the radial thickness of the ring is reduced by five percent, or 31 percent, the piston's resultant mass is reduced by 26.07 percent, and its issue of safety is increased by 3.072 percent. Rao et al. used a piston model to analyze it. Unigraphics and consequences were demonstrated by manufacturing a piston using a vortex technique and aluminum-based mmc containing 5, 10, 15, and 53 micrometer fly ash particulates. We employed the stir casting method to achieve the desired form and complexity, and after casting, the component was machined to achieve the desired shape. The results indicate that this strategy improves the vehicle's performance. It was determined that the modified piston model produces better results than the original model. The stresses were lowered in the modified model, and the piston's burden was reduced, while the piston's reliability was raised. The hardness, wear, and friction are determined by numerous tests performed on it. The issue is how it differs from the original version to the modified version. Vishal et al. did an experimental evaluation of the engine's overall performance; piston materials were derived from the power of the piston's hits. In each of the materials, the maximum stress depth was found on the lowest surface of the piston crown, as expected. The peak of the pistons of 4032 and A2618 absorbed the most displacement. The thermal conductivity of the substances caused the greatest variation in maximum temperature within the piston, and the entire maximum heat flux was absorbed in each of the piston substances. The evaluation of the alloys' results was nearly the same. As a result, additional studies with advanced chemicals and various designing optimization devices may be conducted. Reddy et al. investigated how to improve the engine's performance [8]. It was necessary to investigate the piston. Pistons, which are often constructed of alloy steels, demonstrate the grate's resistance to thermal loads and structural masses. In this project, we used the stable works 2016 software to design a piston, and we used the ANSYS workbench software to evaluate structural load and thermal performance utilizing a variety of materials, including composites, on the piston. Sundaram et al. evaluated a 3-D model that was prepared in CREO, followed by a CAE study using ANSYS 14.5 and the thermal evaluation of three unique materials (Al with 10% SiC, AL with 20% SiC, and AL with 30% SiC) for pistons. According to the ANSYS results, aluminum with 10% SiC material has a higher temperature distribution in each consistent kingdom thermal assessment as well as temporary state thermal evaluation. As a result, aluminium with 10% SiC material is better than aluminum with 10% SiC material. As a result, aluminium alloys with 10% SiC are the best suitable material for pistons. Thermal pressure mitigation is a highly important factor that is answerable to the designing of piston crown or piston head, according to Attar et alstudy .'s and analysis using ANSYS software. The primary focus of this project is to optimize the piston while minimizing piston weight. The piston's substance begins to deteriorate. The piston's optimal result was then acquired. Piston skirts may also appear to deform while in use, resulting in cracks at the piston head's higher end. Because the greatest stress awareness is induced on the higher quit of the piston as a result of deformation, the situation becomes more extreme when the stiffness of the piston isn't always enough, and the crack commonly appears at factor A, which can also expand gradually and even result in splitting alongside the piston vertical. The deformation of the piston is very important for stress distribution on the piston. As a result, the piston crown must be strong enough to reduce distortion in order to limit strain awareness. Aluminium silicon carbide (Al Sic), an aluminium matrix composite, was explored by John et al. as a possible material for aluminium. CATIA v6 was used to create a 3-D model, and ANSYS 14 was used to complete the structural and thermal analysis. AlSiC has superior abrasion resistance, creep resistance, dimensional stability, stiffness-to-weight and strength-to-weight ratios, and extreme temperature ordinary performance when compared to aluminum. The use of AlSiC in piston manufacture is also easier than using aluminum. Devan et al. investigated the temperature distribution of several piston materials. Because the piston is one of the most significant and sophisticated pieces in an IC engine, it is critical to keep it in a precise position in order to keep the engine running smoothly. Thermal circumstances cause pistons to fail in particular. As a result, numerous piston materials were explored in order to find the proper heat distribution. Ordinary heat flux is reduced in AlSiC composite as compared to Al-Si, Al-Mg-Si, and Alloy, according to the evaluation effects of different materials on piston. The maximal heat flux will be reduced by increasing the carbide percentage in AlSiC Alloy. The piston is subjected to unique mechanisms, according to Sonar et althermal .'s research. The allowed strain through which the piston can deform has been calculated. The factors that have the greatest impact on the piston were investigated. The deformation is especially important for the stress distribution at the piston. The sliding and hydrodynamic friction against the cylinder walls hounds it as it turns directions at breakneck speeds. All of these characteristics make a piston small in weight, efficient in changing directions, and capable of maintaining an oil clearance with the cylinder liner throughout typical engine running. A piston is known as a key source of mechanical friction while in motion. To ensure increased engine life, top engine manufacturers propose the use of poly-alpha-olefins based multi-grade

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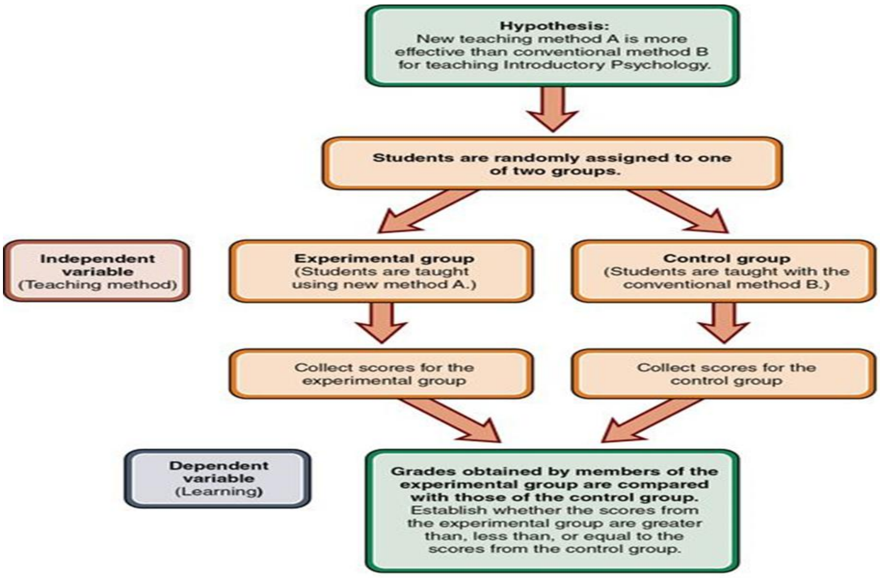


Fig.2 Flowchart of the experimental design

lubricants for smooth normal piston performance. During the first engine start-up, the impact of the piston against the cylinder wall can cause an audible slap sound. During the primary sliding motion of an engine, the piston experiences minor secondary oscillatory displacements in the transverse direction. The engine's performance and dependability are greatly influenced by minor secondary oscillations. During the initial engine cranking and start-up, the hydrodynamic lubrication of the skirts is affected by the oscillatory motion of the piston and its slap. The frictional loss, fuel and oil consumption, engine noise, and start-up wear are all directly related to the mutual dependency between the piston motion and its hydrodynamic lubrication during the first engine start-up. A piston is a dynamically loaded, elastic slider bearing. Because of heat distortion, the piston skirts are designed to work with an interference fit. Due to the low thermal loads during the first engine start-up period, the impacts of such a displacement are not as noticeable. A piston's elastic flexibility allows it to perform effectively. The effects of a piston's elastic flexibility on its hydrodynamic lubrication are studied in electrohydrodynamics, or EHD. Taguchi design is a time and cost-effective method for determining the optimal factor settings with the fewest number of trials possible. The flowchart depicts the steps involved in this Design.

IV.Sensitivity {Slope}-

The slope of I/O characteristics should be at the specified value (usually 1).
It is often treated as Larger-The-Better when the output is a desirable characteristic (as in the case of Sensors, where the slope indicates the sensitivity).
n = 10 Log10 [square of slope or beta of the I/O characteristics] On the other hand, when the output is an undesired characteristic, it can be treated as Smaller-the-Better.
n = -10 Log10 [square of slope or beta of the I/O characteristics]

Linearity (Larger-The-Better)-

Most dynamic characteristics are required to have direct proportionality between the inputand output. These applications are therefore called as "TRANSFORMATIONS". The straight-line relationship between I/O must be truly linear i.e., with as little deviations from the straight line as possible.

$$n = 10 \, \text{Log10} \, \frac{\text{Square of slope or beta}}{\text{variance}}$$

Variance in this case is the mean of the sum of squares of deviations of measured data points from the best-fit straight line (linear regression).The Piston And 1stcompression Ring Lubrication

V.Lubrication in normal engine operation.

The art of lubricating the interacting surfaces of an engine that operates in complicated and time-varying situations includes introducing oil between the piston skirts, rings, and cylinder liner. The fundamental goal of an engine's lubrication system is to keep adhesive and viscous friction to a minimum and to keep the interacting surfaces in relative motion from wearing down. At a few thousand revolutions per minute (rpm), a completely developed electrohydrodynamic lubrication (EHL) coating between the piston and the liner surfaces decreases piston slap and avoids adhesive wear during normal engine operation [8]. In Temperature-related lubricant viscosity fluctuations and deterioration on a regular basis might lead to engine failure [9]. In an engine, lubrication serves to execute the following functions:

1. To reduce wear and friction between the piston, rings, and liner.
2. To create a sufficient lubricant coating between the interacting surfaces of the piston skirts, rings, and liner to carry the fluctuating hydrodynamic and electrohydrodynamic (EHD) loads.
3. To ensure that the piston skirts, rings, and liner are properly sealed.
4. To remove the heat created inside an engine's combustion chamber and cool the piston skirts, rings, and liner surfaces.
5. To clean the surfaces by removing carbon and metal particles that have accumulated due to wear..

VI. Proposed method and result discussion.

The Taguchi technique is a system for analyzing and implementing changes in goods, processes, materials, equipment, and facilities that is scientifically disciplined. By examining the key variables affecting the process and refining the methods or design to provide the best results, these enhancements strive to improve the desired qualities while simultaneously minimizing the amount of faults. The method can be used in a wide range of technical domains, including the production of raw materials, subsystems, and professional and consumer products. In fact, the technology can be used in a variety of processes, including engineering fabrication, computer-aided design, finance, and service industries. The Taguchi approach can be used to 'tune' a process for 'optimal' results. Taguchi developed an eight-step technique for applying his method to any process optimization.

Step 1: Determine the primary function, side effects, and mode of failure.

Step 2: Determine the sources of noise, testing circumstances, and quality attributes.

Step 3: Determine the goal function that has to be improved.

Step 4: Determine the control factors and their magnitudes.

Step 5: Choose an orthogonal array matrices experiment.

6th step: carry out the matrix experiment

Step 7: examine the data and forecast the best levels and performance.

Step 8: carry out the verification experiment and prepare the next course of action using the basic tbc design

A top layer of thermally insulted material and an intermediate bond coat make up the fundamental design. The inter layer, also known as the bond coat, offers sufficient adhesive strength between the ceramic layer and the substrate, as well as acting as an oxidation and corrosion protection barrier. In order to be suitable for thermal barrier coating, the top coat material must have particular qualities. Low thermal conductivity and excellent thermal shock resistance are the most basic requirements among them.

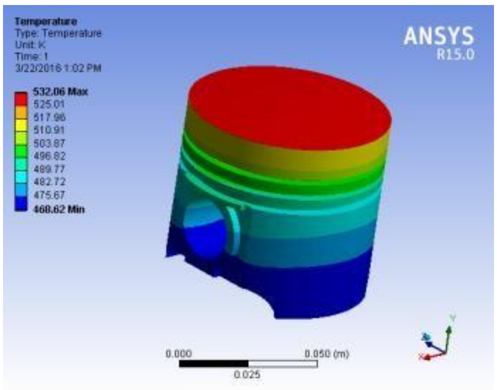
Mullite- Mullite is a significant ceramic material due to its low density, strong thermal stability, low thermal conductivity, chemical stability, and favorable strength and creep properties. Mullite has a substantially lower thermal expansion coefficient, good thermal conductivity, and is much more oxygen resistant than yttria stabilized zirconia. Mullite has a lower thermal expansion coefficient than Y-PSZ, which gives it an advantage in strong temperature gradients and under thermal shock circumstances. SiO2 is abundantly available, inexpensive, and might be used as TBCs. Materials utilized for TBC in Engine Piston Coatings Al2O3: It is extremely hard and chemically inert. When compared to yttria stabilized zirconia, alumina has a higher thermal conductivity and a lower thermal expansion coefficient. Although alumina by itself is not a good thermal barrier coating option, it can be combined with yttria stabilized zirconia to raise the coating's hardness and improve the substrate's oxidation resistance. One of the most commonly utilized ceramic coating materials is Y-PSZ. The use of yttria partly stabilized zirconia has several advantages, including a high thermal expansion coefficient and low thermal conductivity.

. Table 1. Material and Thermal Conductivity

Materials	Thermal conductivity (W/mK)	Coefficient of thermal expansion /K	Density (Kg/m^3)
AlSi	155	0.000023	2700
Al_2O_3	30	0.0000081	3960
Y-PSZ	2.2	0.00001	5650
$Al_6Si_2O_13$	3.3	0.0000053	2800
SiO_2	1.4	0.00000055	2200

VII. Optimization of Temperature.

Based on the nine cases obtained in orthogonal array in Table 2, Finite Element Simulation was carried out in Ansys 15 for high temperature condition of 650K and convection coefficient of 900 W/m2K and shown in Fig



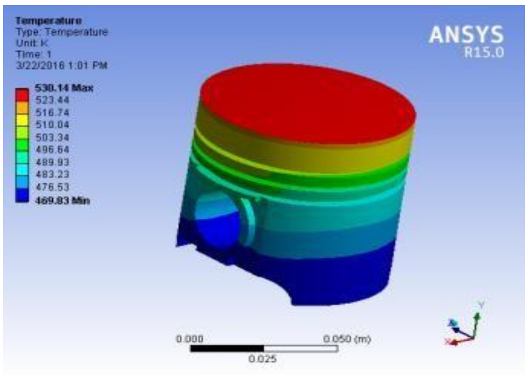


Fig.3 Maximum Temperature

Table 2. Orthogonal Array L-9

S.No.	A	B	C	D
1	250	2.2	0.00001	5650
2	250	3.3	0.0000053	2800
3	250	1.4	0.00000055	2200
4	350	2.2	0.0000053	2200
5	350	3.3	0.00000055	5650
6	350	1.4	0.00001	2800
7	450	2.2	0.00000055	2800
8	450	1.4	0.00001	2200
9	450	3.3	0.0000053	5650

trial runs or orthogonal array can be obtained using the following expression: N-Taguchi = 1+NV (L 1) (1), Where NV is the number of variables, L is the number of levels and N-Taguchi is the total number of trial runs. Here, NV=4 and L=3.Therefore N-Taguchi = 9.The most suitable orthogonal array for experimentation is L9 array as shown in Table2. As a result, a total of nine tests will be conducted. The Taguchi method is an optimization strategy that is based on the number of experiment trials conducted for various control elements. Experimental trials are carried out using an orthogonal array, which allows us to see the effect of different control parameters in a small number of trials, allowing us to find the best level parameter. Bond coat, also known as adhesive coat, provides sufficient adhesive strength between the ceramic layer and the substrate, as well as acting as an oxidation and corrosion protection barrier. In order to be suitable for thermal barrier coating, the top coat material must have particular qualities.

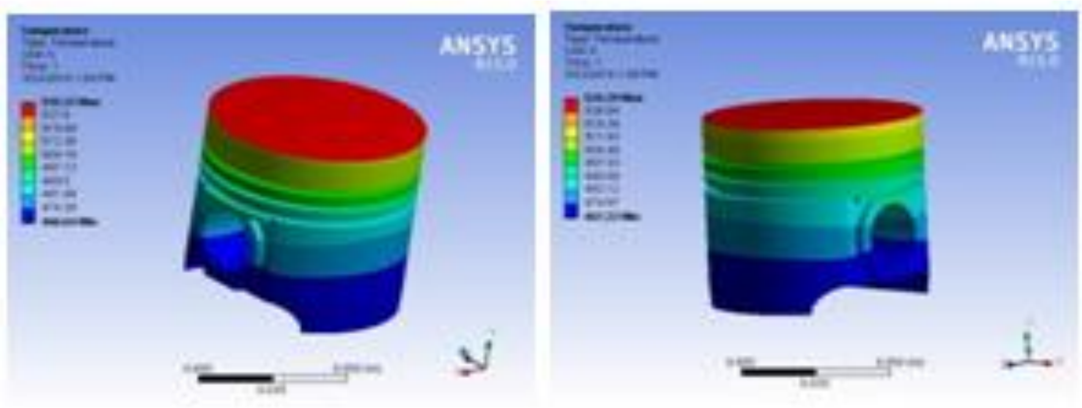


Fig.4 Maximum Temperature on Piston and Minimum Temperature

Taguchi method stresses the importance of studying the response variation using the signal–to–noise (S/N) ratio, resulting in maximization of quality characteristic variation due to uncontrollable parameter.The maximum temperature on the piston was considered as the quality characteristic with the concept of "the larger-the-better". The S/N ratio for the larger-the-better is: S/N= -10 log10{1/n∑1/y2} (2) Where n is the number of measurements in a trial, in this case, n=1 and y is the measured value in a run[5]. The S/N ratio values are calculated by taking into consideration Eqn(2)with the help of software Minitab. The values measured from the experiments and their corresponding S/N ratio values are listed in Table 4. From these values, graphs are obtained in software itself which shows the variation of mean of S/N ratios with the coating thickness (A), thermal conductivity (B), coefficient of thermal expansion(C) and density (D) respectively in Fig 2. From these linear graphs it is clear that the optimum values of the factors and their levels are as given in table 5. Regardless of the category of the performance characteristics, a greater S/N ratio value corresponds to a better performance.

A	B	C	D	Max Temp(K)	S/N Ratio
250	2.2	0.00001	5650	532.06	54.5192
250	3.3	0.0000053	2800	530.14	54.4878
250	1.4	0.00000055	2200	535.22	54.5706
350	2.2	0.0000053	2200	534.29	54.5555
350	3.3	0.00000055	5650	531.68	54.513
350	1.4	0.00001	2800	538.51	54.6239
450	2.2	0.00000055	2800	536.43	54.5903
450	1.4	0.00001	2200	533.18	54.5375
450	3.3	0.0000053	5650	541.62	54.6739

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