Geometry design and optimization of piston by using finite element method

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Abstract. The piston performance may be impacted by piston geometry, stress, temperature and deformation applied. Thus, the purpose of this study is to investigate the changes of piston performance with different piston head designs. Besides, the piston is optimized by using topology optimization to remove excessive material. The study was carried out by using the dimension of a piston based on the cylinder of a spark ignition engine. The four piston head designs are flat-top piston, bowl piston, square bowl piston and dome piston. All four piston designs were modelled by using Solidworks. Static Structural and Steady State Thermal Analysis in ANSYS Workbench were used to analyze the piston performance. The measured parameters are stress, deformation and temperature distribution. Next, optimization of piston was done by using topology optimization to identify non-essential parts that can be removed. The optimized piston design was analyzed. The findings for the original and optimized piston geometries were tabulated to make comparison. It is found that bowl piston has lower stress, deformation and temperature. The stress, deformation and temperature of optimized piston is lower than original piston. The mass of optimized piston is about 5 percent less than the original piston.

1. Introduction

Internal combustion engine is the essential component of a vehicle which is used as propulsion of the vehicle. Piston is one of the most important components of the engine. It has a cylindrical shape and it reciprocates back and forth in cylinder. It transmits force to the rotating crankshaft for the output of engine. It needs to withstand high pressure and temperature due to combustion [1-2]. The occurrence of fatigue failure on piston due to high stress and thermal load is not uncommon. Fatigue failure of piston may lead to reduction of engine power, overheating of engine and maintenance cost will be required from owner to repair or replace the faulty piston [3].

Thus, a piston needs to be designed to have low stress and temperature when operating. Recent study has shown that the amount of stress and temperature are affected by the shape of piston crown [4]. Selection of suitable piston crown decreases the temperature and stress on piston so that the piston will last longer. One of the methods to analyze piston is Finite Element Method (FEM), which used to simulate piston models under operating conditions and obtain values of stress, temperature and...
deformation. Physical prototype is not essential using FEM and this may saves time and cost. Static structural and steady state thermal analysis in ANSYS are able to show the distribution of stress, temperature and deformation after applying the boundary condition. Studies show that the highest stress, temperature and deformation occur at the top surface of piston crown since combustion occurs near this surface [5-6].

A piston with longer service lifetime is always desirable. This can be achieved if the deformation and stress on piston when operating is reduced. Optimization of piston by removing excessive piston material is able to reduce piston material and material cost. Previous studies have shown that removing excessive piston material is able to reduce the stress and deformation on the piston [7-8]. However, similar research by Bagul and Tripathi [9] showed that the stress and deformation of optimized piston with reduced mass have increased. Analysis needs to be carried out to determine whether removing excessive material is able to reduce the stress and deformation on piston. One of the effective methods to remove material is by using Topology Optimization (TO) in ANSYS Mechanical. Elements of model which have low stress will be identified and removed using TO. The target percentage of mass reduction can be set in TO. A study about TO of piston has been conducted by Gaidur et al. [10]. In this study, there is 1 % of reduction in piston mass and 17% reduction in Von Mises stress on optimized piston compared to original piston.

Fatigue failure is still a common issue for piston and reduction of piston cost is always appreciable. Hence, the objectives of this study are to identify the effect of different piston crown shapes on equivalent stress, total deformation and temperature on piston and determine the piston crown shape which gives lower values of these parameters. This study also determines the optimized piston design by using TO, in order to remove excessive piston material.

2. Methodology

This study involves the design and modelling of four piston geometries using Solidworks. After that, the temperature, deformation and stress distribution of these piston geometries were analysed by using ANSYS, and design optimization of the piston by using TO.

2.1. Designing and Modelling of Pistons

The pistons designed in this study are used for Spark Ignition (SI) engine since they are designed based on specification and characteristics of a SI engine. The specification of the SI engine is shown in Table 1 [11].

| Specification          | Values       |
|------------------------|--------------|
| Bore × stroke (mm)     | 87.5×103.4   |
| Displacement (cc)      | 2487         |
| Compression ratio      | 13           |
| Max power (kW)         | 151          |
| Max torque (Nm)        | 250          |

The common materials for pistons are cast iron and aluminum alloy. The selection of material is based on magnitude of piston speed. Cast iron is suitable for pistons with piston speed lower than 6 m/s, while aluminum alloy is suitable for pistons with piston speed higher than 6 m/s [12]. The piston speed is calculated as shown in Eq.1 for 2000 rpm, where RPM is defined as rotation per minutes.
Piston speed = 2 × Stroke × RPM

The calculated piston speed is higher than 6 m/s, hence aluminum alloy is chosen as the material of piston in this study. More specifically, Aluminum Alloy 4032 is the material of piston since it is widely used as material for manufacturing pistons due to its lightweight, good corrosion resistance and durability [13]. The main variable which needs to be analyzed in this study is the shape of piston head. Thus, the piston head shape of all four piston models are different and all other dimensions for all piston models are identical. Before modelling the pistons, the dimensions of all parts of the piston need to be determined first. Figure 1 shows the nomenclature of a general piston geometry.

![Figure 1. Nomenclature of Piston Geometry [12]](image)

The equations Eq. 2-11 were used to calculate the dimensions of piston shown as below [12]. The calculated dimensions are shown in Table 2.

Thickness of piston head \( t_H = D \sqrt{\frac{3}{16} \times \frac{P}{\sigma_b}} \)  

where \( D \) is cylinder bore (87.5 mm), \( P \) is maximum pressure (5 MPa) and \( \sigma_b \) is allowable bending stress of piston (70 MPa) [12].

Radial thickness of ring \( t_1 = D \sqrt{\frac{3 P_w}{\sigma_t}} \)  

where \( P_w \) is defined as the pressure of fuel on cylinder (0.042 MPa) and \( \sigma_t \) is the permissible tensile stress for ring material, 100 MPa [12].

Minimum Axial thickness of ring \( t_2 = \frac{D}{10z} \)  

where \( z \) = number of rings
Top land thickness $b_1 = 1.2 \ t_1$  

Thickness of other land $b_2 = 0.75 \ t_2$  

Maximum thickness of barrel $t_3 = 0.03D + t_1 + 0.4 + 4.5$  

Thickness of piston barrel at lower end, $t_4 = 0.3 \ t_3$  

Length of piston pin at the bush of small end of connecting rod, $l_1 = 0.45 \ D$  

To determine outer diameter of piston pin, $d_o$, it is calculated as:

$$\frac{\pi D^2}{4} P = P_b \times d_o \times l_1$$

where $P_b$ is bearing pressure at small end of connecting rod (25 MPa).

### Table 2. Dimensions of Piston

| Parameters                                      | Values   |
|------------------------------------------------|----------|
| Thickness of piston head, $t_0$ (mm)            | 10.126   |
| Radial thickness of ring, $t_1$ (mm)            | 3.10594  |
| Minimum axial thickness of ring, $t_2$ (mm)     | 2.91667  |
| Top land thickness, $b_1$ (mm)                  | 12.1512  |
| Thickness of other land, $b_2$ (mm)             | 2.1875   |
| Maximum thickness of barrel, $t_3$ (mm)         | 10.63094 |
| Thickness of piston barrel at lower end, $t_4$ (mm) | 3.189    |
| Length of piston pin at the bush of small end, $l_1$ (mm) | 39.375   |
| Outer diameter of piston pin, $d_o$ (mm)        | 30.54    |

After calculating the dimensions of the piston, the four types of piston head shapes are determined based on related studies. The four analyzed piston designs are flat-top piston, bowl piston, square bowl piston and dome piston since these piston designs are commonly used in the industries and they affect the combustion in cylinder differently which results in different deformation, temperature and stress distribution for different pistons [14]. All four piston designs are modelled using Solidworks based on the dimensions calculated.

![Figure 2. Modelling of Four Pistons (a) Flat-Top Piston, (b) Bowl Piston, (c) Square Bowl Piston (d) Dome Piston.](image-url)
As the name suggests, flat-top piston has a flat piston head shape. This type of piston is easier to manufacture compared to other piston designs and its manufacturing cost is also lower. Figure 2(a) shows the modelling of flat-top piston in Solidworks. Bowl piston has a circular recess on the piston crown. A vortex of air and fuel can be created in the cylinder due to the piston bowl which results in more efficient combustion. The modelling of bowl piston in Solidworks is shown in Figure 2(b). The diameter of the bowl is 60 mm with depth of 7 mm. Square bowl piston has a square recess on the piston crown. The rounded corners create turbulence which helps in air-fuel mixing. Figure 2(c) shows the modelling of square bowl piston in Solidworks. The length of each side of square bowl is 52 mm with depth of 7 mm. There is an additional volume on the top surface of piston crown of dome piston. This increases the compression ratio and the power output. Figure 2(d) shows the model of dome piston in Solidworks. The maximum height of the dome is 8 mm.

2.2. Analysis of Four Pistons

Before analyzing the pistons using ANSYS Workbench, the models of all four piston geometries need to be saved as IGS file so that these models can be imported to ANSYS. The analysis systems used in ANSYS for this study are Static Structural and Steady State Thermal analysis since the loads applied on piston do not change with time. The properties of Aluminum Alloy 4032 used in the analysis are shown in Table 3.

| Property                               | Magnitude       |
|----------------------------------------|-----------------|
| Young's Modulus (GPa)                  | 82              |
| Poisson Ratio                          | 0.33            |
| Coefficient of Thermal Expansion (1/°C)| $1.94 \times 10^{-5}$ |
| Tensile Ultimate Strength (MPa)        | 370             |
| Tensile Yield Strength (MPa)           | 315             |
| Density (kg/m³)                        | 2700            |

After the material and piston geometry have been set, the boundary conditions of piston need to be applied in ANSYS Mechanical to simulate its operating conditions. The boundary conditions for all four types of pistons are the same. Under Static Structural analysis, 5 MPa of pressure is applied on top surface of piston head [16]. This pressure is due to combustion of gases in cylinder. Since piston reciprocates vertically in the cylinder, frictionless support is applied at the outer surface of piston to prevent it from moving in the normal direction. Frictionless support is also applied at piston pin bore since the pin rotates freely in the bore. A displacement boundary condition is applied on top surface of piston head. The x and z components of this displacement are set as zero while the y component is set as free so that the piston is able to move freely in the y (vertical) direction. All the boundary conditions of piston applied in ANSYS under Static Structural are shown in Figure 3.
For the boundary conditions in Steady State Thermal analysis, the temperature of top surface of piston head is set as 330 °C since this surface is exposed to the combustion [16]. Heat transfer by convection occurs between the piston and the oil film which can be found between piston and cylinder. Different parts of piston have different heat transfer coefficient. Table 4 shows the values of heat transfer coefficient for different parts of piston [6]. These values are set in ANSYS as the boundary condition. Figure 4 shows the boundary conditions of piston in ANSYS under Steady State Thermal analysis.

| Part of Piston | Heat Transfer Coefficient (W/m² K) |
|---------------|-----------------------------------|
| Piston Head   | 300                               |
| Top Land      | 160                               |
| Piston Ring   | 120                               |
| Piston Skirt  | 600                               |

The next step is to determine the suitable mesh method and mesh sizing for the analysis of piston in ANSYS in order to obtain accurate results. Two mesh methods are compared, which are Tetrahedron and Hex Dominant. The values of skewness and orthogonal quality, which can be obtained from...
ANSYS, are used to determine the mesh quality. Generally, lower skewness and higher orthogonal quality give better mesh quality. Table 5 shows the values of skewness and orthogonal quality of mesh of flat top piston for both methods. Based on Table 5, the mesh of flat top piston using Tetrahedron method has lower skewness and higher orthogonal quality, compared to Hex Dominant. Hence, Tetrahedron is used as the mesh method for the analysis of piston since it shows better mesh quality.

| Method         | Element Size (m) | Skewness | Orthogonal quality |
|----------------|------------------|----------|--------------------|
| Tetrahedron    | 0.006            | 0.42475  | 0.5739             |
| Hex dominant   | 0.006            | 0.6257   | 0.43111            |

Generally, smaller mesh sizing increases the accuracy of results, but the computing time increases too. Mesh independence test is conducted to determine the suitable mesh sizing which gives sufficiently accurate result without consuming too much computing time. The total deformation and equivalent stress of flat top piston using mesh sizing ranging from 0.008 m to 0.0035 m are obtained and compared. Table 6 shows values of total deformation and equivalent stress obtained from ANSYS for different element size.

| Element size (m) | No Element | Total Deformation (m) | % difference of deformation | Equivalent Stress (Pa) | % difference of equivalent stress |
|------------------|------------|-----------------------|----------------------------|------------------------|----------------------------------|
| 0.0080           | 7852       | 1.1985E-04            | -                          | 3.7325E+08             | -                                |
| 0.0075           | 9341       | 1.2072E-04            | 0.73                       | 3.7617E+08             | 0.78                             |
| 0.0070           | 9924       | 1.2094E-04            | 0.18                       | 3.7522E+08             | -0.25                            |
| 0.0065           | 10859      | 1.2340E-04            | 2.03                       | 3.8160E+08             | 1.70                             |
| 0.0060           | 12409      | 1.2527E-04            | 1.52                       | 3.8648E+08             | 1.28                             |
| 0.0055           | 14327      | 1.2601E-04            | 0.59                       | 3.8975E+08             | 0.85                             |
| 0.0050           | 17038      | 1.2984E-04            | 3.04                       | 3.9765E+08             | 2.03                             |
| 0.0045           | 21160      | 1.3305E-04            | 2.47                       | 4.0535E+08             | 1.94                             |
| 0.0040           | 28329      | 1.3566E-04            | 1.96                       | 4.1043E+08             | 1.25                             |
| 0.0035           | 42402      | 1.3598E-04            | 0.24                       | 4.1269E+08             | 0.55                             |

Based on Table 5, Figure 5 and Figure 6, after the element size is decreased to 0.004 m and the number of elements is 28329, there is not much difference in the total deformation and equivalent stress if the element size continues decreasing. This implies that if the element size is smaller than 0.004 m, the element size will not have much effect on the result. The accuracy of result will only increase by small amount, but the computing time will become longer. Thus, the chosen element size in this study is 0.004 m.
Tetrahedron mesh method and element size of 0.004 m are applied on all four types of piston for fair comparison. The temperature, deformation and equivalent stress of all four piston models are obtained from ANSYS and used to make comparison.

After that, TO is carried out on the piston which has lowest temperature, deformation and stress to further optimize this piston. Exclusion regions need to be set in TO so that important parts of piston are not removed and the functions of piston are maintained. These regions include top surface of piston head, outer surface of piston and piston pin bore. The type of response constraint in TO is set as mass to reduce the mass of piston. Another model of piston is created using Solidworks based on result of TO. The optimized piston model is also analyzed using ANSYS and compared to original piston model.

3. Result and Discussion

A piston with lower stress, deformation and temperature has longer service lifetime. Thus, the values of these parameters for all four types of pistons are obtained from ANSYS and are shown in Table 7.
Based on Table 7, there is no difference in minimum temperature among all four pistons. Bowl piston has the lowest average temperature while dome piston has the highest average temperature. This is due to the more efficient combustion and faster burning rate of air-fuel mixture on bowl piston compared to dome piston [14]. Faster burning rate means that the air-fuel mixture is burned completely in a shorter amount of time. This show that bowl piston has a better thermal performance during the combustion process.

The temperature distribution of piston is similar for all four types of piston as shown in Figure 7. The piston has the highest temperature at 330 °C at the piston head since combustion occurs at this surface. The temperature decreases from top region to bottom region of piston where it is far from the combustion. The minimum temperature is around 83 °C for all four pistons. Calbureanu et al. [16] also showed similar results with maximum temperature of 330 °C at piston head of a flat-top piston and the temperature decreases to 133 °C at bottom region of piston based on their study.

![Figure 7. Temperature Distribution of Four Pistons from ANSYS. (a) Flat-Top Piston, (b) Bowl Piston, (c) Square Bowl Piston (d) Dome Piston](image-url)
Total deformation shows the amount of displacement experienced by any part of the piston under the pressure applied. According to Table 7, dome piston has the highest average and maximum total deformation, followed by flat top piston and square bowl piston, bowl piston has the lowest average and maximum total deformation. In other words, the dome piston deforms the most while bowl piston deforms the least under the same pressure applied. This indicates that bowl piston has higher resistance to changes in shape or size when pressure is applied compared to other types of pistons. This is desirable since a piston needs to operate for long period of time and its quality must be maintained. Changes in size or shape of piston will result in reduction of engine power.

As shown in Figure 8, the maximum total deformation occurs at the top surface of piston head for all four types of piston. This is because pressure is applied directly on this surface. Low deformation occurs at the piston pin bore region because this region is supported by piston boss at the inner surface of piston. To validate the findings, the value of maximum total deformation is compared to values obtained from other study. The study by Sonar and Chattopadhyay [17] shows that the maximum total deformation of an Aluminum Alloy flat top piston is 0.5 mm, which is slightly different to the maximum total deformation of 0.36 mm obtained in the current study. The difference might be due to the different dimensions of piston analyzed. The finding in this current study is considered valid since the difference of result between this study and other study is not significant.

Figure 8. Total deformation of four piston from ANSYS. (a) Flat-Top Piston, (b) Bowl Piston, (c) Square Bowl Piston and (d) Dome Piston

Equivalent (von-Mises) stress obtained from ANSYS is used to determine whether the piston will yield or not. Based on Table 6, dome piston has the highest average equivalent stress (433 MPa) but it also has the lowest maximum equivalent stress (870 MPa). Square bowl piston has the highest maximum stress (978MPa) while bowl piston has the lowest average stress (398 MPa).

As shown in Figure 9, the high equivalent stress is also found at the piston head where the gas pressure is applied. The maximum stress occurs at inner surface of piston head. However, the yield
strength of Aluminum Alloy 4032 is 315 MPa. The maximum equivalent stress of all four pistons are higher than this yield strength. This shows that the pistons will deform plastically under the loads applied. The maximum equivalent (von-Mises) stress of an Aluminum Alloy 4032 flat-top piston found by Vishal, Jain, and Chauhan [18] is 238 MPa, which is lower than the maximum stress obtained in current study. This shows that the dimension and design of the pistons in this current study are not suitable for the pistons to operate. Optimization must be done to improve the design and reduce the stress on piston.

![Figure 9](image_url)  
Figure 9. Equivalent (von-Mises) stress of four pistons from ANSYS. (a) Flat-Top Piston, (b) Bowl Piston, (c) Square Bowl Piston and (d) Dome Piston

Overall, the temperature, deformation and stress of bowl piston under the operating conditions are lower. This implies that bowl piston shows better thermal and mechanical performance. The probability of occurrence of fatigue failure for bowl piston will be lower since it has lower temperature, deformation and stress. Thus, it has longer service lifetime.

Topology Optimization (TO) is carried out to remove excessive piston material and reduce the mass of piston. Bowl piston is optimized using TO. As shown in Figure 10, most of the piston material removed is the inner part of piston barrel thickness. The top surface of piston head, outer surface of piston and piston pin bore are not removed since these parts are set as exclusion regions and they must be retained to maintain the function of piston. Another model of bowl piston is built based on the result of TO.
For the optimized bowl piston, the maximum thickness of piston barrel is reduced from 10.63 mm to 7 mm. Since high stress and deformation occurs at piston head, the thickness of piston head is increased from 10.13 mm to 13.5 mm to strengthen the piston head. Based on Solidworks, the mass of original bowl piston is 437 g while the mass of optimized bowl piston is 412 g. Even though the thickness of piston head is increased, the mass of optimized bowl piston has decreased by about 5 percent compared to original bowl piston due to the reduction of maximum thickness of barrel. The optimized bowl piston is analyzed using ANSYS and its result is compared to original bowl piston. Table 8 shows the comparison of results between original bowl piston and optimized bowl piston.

| Parameters          | Original bowl piston | Optimized bowl piston |
|---------------------|----------------------|-----------------------|
| Average deformation (m) | 1.2345E-04          | 2.4456E-05            |
| Max deformation(m)  | 3.3881E-04          | 5.8456E-05            |
| Average stress(Pa)  | 3.9756E+08          | 2.2064E+07            |
| Max stress(Pa)      | 8.9617E+08          | 1.2997E+08            |
| Average Temp (°C)   | 2.2448E+02          | 2.1622E+02            |
| Min Temp (°C)       | 8.3479E+01          | 7.3183E+01            |

Based on Table 8, the deformation, stress and temperature of optimized bowl piston are lower than original bowl piston. The maximum stress on optimized piston is less than the yield strength. The optimized piston will not yield. The increment in dimension of thickness of piston head has reduced the stress on piston. The material removal using TO do not worsen the performance of piston since the parts of material removed does not affect the operation and function of piston. The application of TO has reduced piston material and material cost. This shows that TO is an effective method to remove excessive material without affecting the functions of piston.

There are some limitations in this study. Firstly, the main objective of this study is to show how different piston head shapes affect stress, deformation and temperature. The effect of different dimensions of bowl, square bowl and dome on performance of a piston is not considered in this study. Next, ANSYS only provides approximate results by using the simulated model. There might be differences between operation of actual piston and simulation of piston in ANSYS.
4. Conclusion

It is shown that the temperature, total deformation and equivalent (von-Mises) stress of bowl piston are lower. Bowl piston has longer service lifetime under the loads applied. However, the stress on all four original pistons is higher than yield strength, which shows that the pistons will yield. TO is carried out to remove excessive material. The optimized bowl piston has smaller barrel thickness but larger piston head thickness. All the values of temperature, deformation and stress for optimized bowl piston are lower than original piston. The mass of optimized piston is also lower. The optimized piston has better thermal and mechanical performance with lower mass. This proves that TO removes excessive material effectively. Possible future study is to work on comparing few topology optimized pistons with different mass reduction percentage and determine the maximum percentage of mass reduction a piston can achieve.

5. References

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