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Design, Thermal Stress Analysis and Performance Optimisation of Marine Diesel Engine Piston

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ABSTRACT
This study presents a thermal stress analysis and performance optimization of a Marine Diesel Engine (MDE) piston. The study is necessitated by the need to optimise piston design so as to mitigate thermal stress induced failure. The operation of MDE piston is described along with its thermal and geometric properties. Thermal stress on the piston done using ANSYS tool. Geometric parameters of the piston are evaluated and optimised using performance data. Experiment: MDE stress max 6408.6 MPa at crown. MDE minimum stress 270.05MPa at skirt. Von-mises stress 85.6439MPa, 55.6685MPa and 69MPa. Width of the top land 10.84mm, 9.36mm and 10mm. the deflections on the MDE piston are 0.051762mm, 0.025884mm and 0.05884mm at the respective piston axial thickness of 5mm, 3.52mm and 4mm.

From the research, it is found that an improper piston skirt design could cause severe thermal stress, wear of moving components, crack of skirt, etc. The largest thermal stress concentration occurs on the piston crown. In conclusion, with optimal mathematical model, the MDE piston Experiences a maximum temperature of 2179.6^{o}c at crown and a minimum temperature of 80.89^{o}c at skirt.

Keywords:ANSYS, FEA, CFA,ThermalStress, Piston, Stress concentration, Optimization,

1. INTRODUCTION

The requirements for high-speed Marine vessels with low specific fuel consumption (SFC) at reduced emission and other factors are the design considerations for selecting a power plant. The major power plant, widely used for both water and land transportation, is a diesel engine. It is probably preferred due to the high power developed per unit weight compared to other power plants. This is with corresponding increase in power output (Matteo et al., 2014). Alternative power plants are steam turbine, gas turbine and nuclear power plant, etc.

The engine components can easily experience failure if proper design is not taken into consideration. Hence, this work adds credence to previous works in the area of optimisation and improvement of the design of piston for Marine Diesel Engine (MDE). This is to enhance its reliability and robustness.

It is found that the ratio of the piston height to the diameter is observed to be decreasing due to the improvements in modern design. The progressive reductions in piston height and circumferential extent of its skirt imply corresponding reduction in the piston mass. This is also a consequent decrease in the inertial forces. This also results in lesser friction losses and fuel consumption (Matteo et al., 2014).

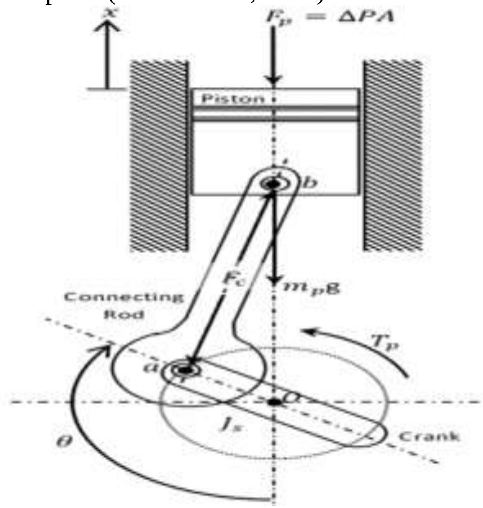

Fig. 1: Simplified internal components of MDE (Murphy, et al., 2015)

More so, in the design of mechanical components, the major focus has always been on the mechanical stress analysis of parts as it is very much crucial in the determination of the geometry

of such parts. Lesser attention is given to the aspect of thermal stress analysis (Calbureanu, et al., 2013). This is presumably due to its lesser effects in the design of components of an MDE. However, the drastic reduction in the size of modern MDE has mandated a more thorough investigation into the stress caused by thermal transfer especially to the piston. There are many different forms of damage mechanism that may affect the engine piston strength, namely; wear and tear, high temperature and fatigue (Matteo et al., 2014). Fatigue phenomena is identified Flowedayet al., (2011). Thus, this research is focused on investigating the Mathematical Modelling of thermal stress of the piston with a view to employing available computational code for the analyses. It investigates the several aspects of optimisations. Not only this, but adopts a more modern method of design for efficient performance of the
components of interest.

II. DATA ANAYLSIS

The design of the piston starts with the definition of the piston geometry using 3D CAD software. This 3D CAD geometric model is then imported to FEA software and analysed under the predicted service conditions before anything is made. That speeds up the design and testing process. It decreases the lead time to create new pistons designs, and produces a better product. The idea behind finite analysis is to divide a model piston into a fixed finite number of elements. Computer software generates and predicts the overall stiffness of the entire piston.

Analysis of the piston is done to optimise the stresses and minimize the weight using ANSYS. The Mathematical Model of optimisation is established first and the FEA is carried out by using the ANSYS software. Based on the analysis of optimal result, the stress concentration on the piston is evaluated, which provides a better reference for re-designing of piston.

III. MATERIALS AND METHODS

The following are materials used in this piece of work. Aluminium-Silicon (Al-Si) alloys whose permissible stress were found to be in the range of 50- 90MPa. The specified piston length is 152mm and the piston diameter is 140mm. In this research, FEA of heat transfer and residual stress in the marine diesel piston will be carried out and compared to experimental data generated during the current research. There are many FEM software programs available to proffer various engineering solutions. However, the ANSYS finite element program will be used in the current research.

This is because it is widely available within the University. Hence the afore-mentioned data are specific to the ANSYS program. The design of the piston starts with the definition of the piston geometry using 3D CAD software. This 3D CAD geometric model is then imported to FEA software and analysed under the predicted service conditions before anything is made. That speeds up the design and testing process, reduces the lead time to create new pistons design, and produces a better product. The idea behind finite analysis is to divide a model piston into a fixed finite number of elements. Computer software generates and predicts the overall stiffness of the entire piston. The analysis of the piston with ANSYS is done to optimise the stresses and minimize the weight. The Mathematical model of optimisation is formulated first, then FEA results on ANSYS software are correlated for validation. Based on the analysis of optimal result, the stress concentration on the piston would provide a better reference for re-designing of the piston.

Design ofMDE Piston

The piston is designed according to the procedures and specifications which are given in machine design and data handbooks. The dimensions are calculated in terms of S.I. Units. The pressure applied on piston head, temperatures of various areas of the piston, heat flow, stresses,strains, length, diameter of piston and hole, thicknesses, etc., parameters are taken into consideration.

Design Considerations for a Piston

The following factors are made:

- ❖ It should have enormous strength to withstand the high pressure.
- ❖ It should have minimum weight to withstand the inertia forces.
- ❖ It should form effective gas sealing in the cylinder.
- ❖ It should provide sufficient oil lubrication to prevent undue wear.
- ❖ It should have high speed reciprocation without noise.
- ❖ It should be of sufficient rigid construction to withstand thermal and mechanical distortions.
- ❖ It should have sufficient support for the piston pin.

Procedure for Piston Design parameters:

The procedure for piston design consists of the following steps:

- ❖ Thickness of piston head (t_H)
- ❖ Heat flows through the piston head (H)
- ❖ Radial thickness of the ring (t_1)

- Axial thickness of the ring (t_2)
- Width of the top land (b_1)
- Width of other ring lands (b_2)

A. Piston Design Parameters:

The parameters for a piston design consist of the following:

(i) Thickness of piston head (t_H)
(ii) Heat flows through the piston head (H)
(iii) Radial thickness of the ring (t_1)
(iv) Axial thickness of the ring (t_2)
(v) Width of the top land (b_1)
(vi) Width of other ring lands (b_2)

(i) Thickness of Piston Head (t_H):

Thickness of the piston head is calculated using Grashoff's formula:

$$t_H = D\sqrt{\left(\frac{3}{16}\right)\cdot\left(\frac{P}{\sigma_t}\right)} \quad (1)$$

Where:
P = maximum pressure in N/mm²
D = cylinder bore/outside diameter of the piston in mm.
σt = permissible tensile stress for the material of the piston.

Here the material is a particular grade of AL-Si alloy which permissible stress is 50 MPa- 90Mpa. Before calculating thickness of piston head, the diameter of the piston has to be specified. The given piston length is 152mm and the piston diameter is 140mm.

(ii) Heat Flow through the Piston Head (H):

The heat flow through the piston head is calculated using the formula

$$H = 12.56 \times t_H \times K \times (T_C - T_e) \quad (2)$$

Where:
K = Thermal conductivity of material which is 174.15W/mk
Tc = temperature at centre of piston head in °C.
Te = temperature at edges of piston head in °C.

(iii) Radial Thickness of Ring (t_1)

$$t_1 = D\sqrt{\frac{3 \times P_w}{\sigma_t}} \quad (3)$$

Where:
D = cylinder bore in mm
P_w = pressure of fuel on cylinder wall in N/mm². Its value is limited from 0.025N/mm² to 0.042N/mm². For present material, σt is 90Mpa

(iv) Axial Thickness of Ring (t_2)

The thickness of the rings may be taken as $t_2 = 0.7t_1$ to t_1. Let us assume t_2 = 5mm
Then the minimum axial thickness (t_2)

$$t_2 = \frac{D}{10 \times n_r} \quad (4)$$

Where: n_r = number of rings

(v) Width of the top land (b_1)

The width of the top land varies from, $b_1 = t_H$ to $1.2 \times t_H$ (5)

(vi) Width of other lands (b_2)

Width of other ring lands varies from, $b_2 = 0.75 \times t_2$ to t_2 (6)

(vii) Maximum Thickness of Barrel (t_3)

$t_3 = 0.03 \times D + b + 4.5$mm (7)
Where: b = radial depth of piston ring groove
Also, $b = t_1 + 0.4$ (8)

Table 1: Design Specification before optimisation(Source: Manufacturer's manual of the MDE onboard MT Otuoke in NPA, Rivers Port)

S/No	Design1 – Dimensions	Size(mm)
1	Length of the Piston(L)	152
2	Cylinder bore/outside diameter of the piston(D)	140
3	Radial thickness of the ring (t_1)	5.24
4	Axial thickness of the ring (t_2)	5
5	Maximum thickness of barrel (t_3)	14.34
6	Width of the top ring land (b_1)	10.84
7	Width of other ring lands (b_2)	4

Table 2: Thermal and Geometric Properties Of MDE Piston

Property	Aluminium Alloy	Zirconium
Young's Modulus	70×10^3MPa	220×10^3 MPa

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Poisson's Ratio	0.31	0.35
Thermal Conductivity	234W/mk	7W/mK
Co-efficient of thermal Expansion	23 x 10^{-6}/K	10 x 10^{-6}/K

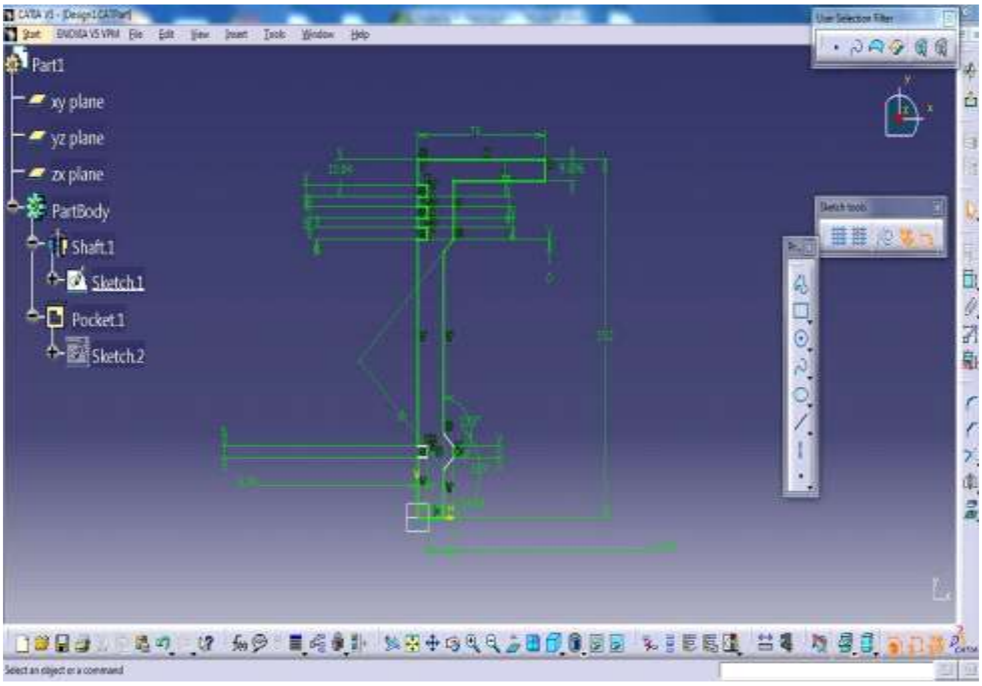

Fig. 2: Sketch of the Piston before optimization

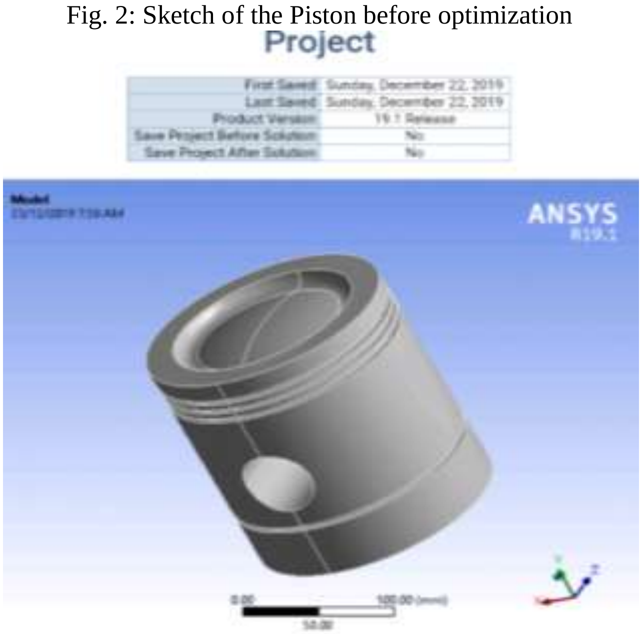

Fig. 3: Piston Model

IV. RESULTS AND DISCUSSION

The current model is undergone through Thermal Analysis and followed by Static Analysis, together known as Coupled Field Analysis. The meshed component is analysed to find the thermal stresses of the piston. The component is subjected to the influence of heat conduction at the top of the piston and heat convection to side lands. The following images are shown for result deformation and Von-Misses stresses before and after optimisation.

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A. Total Deformation

The MDE piston experiences a maximum total deformation of 2.4187mm at the piston crown and a minimum total deformation of 0.0094155mm at the skirt. This is as a consequence of the influence of heat conduction at the top of the piston and heat convection to side lands as revealed in Fig. 4.

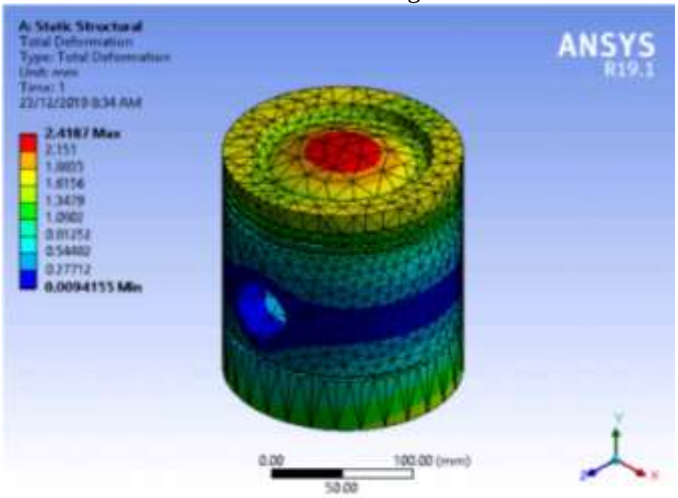

Fig. 4: Total deformation of the MDE piston

B. Directional Deformation

The MDE piston experiences a maximum directional deformation of 0.39843mm and a minimum directional deformation of -0.39943mm as shown in Figure 5.

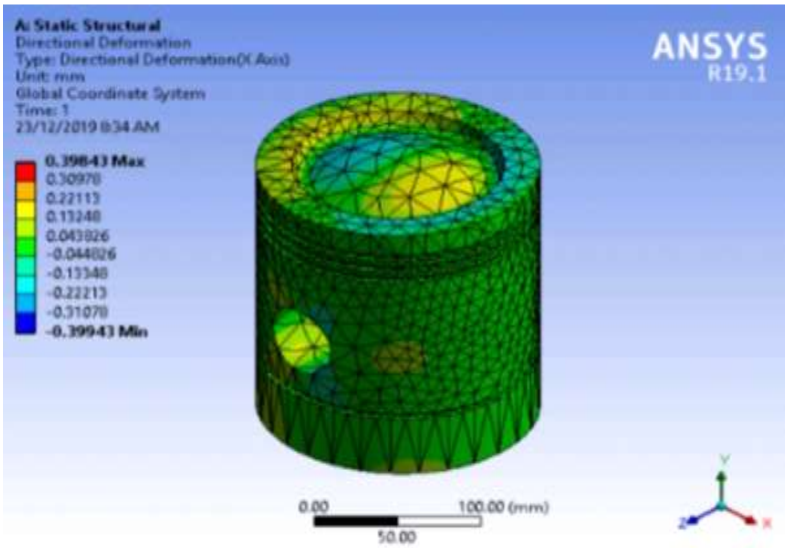

Fig. 5: Directional Deformation of the MDE piston

C. Total Heat Flux

The MDE piston experiences a maximum total heat flux of 23.941W/mm^2 at the piston crown and a minimum total heat flux of 0.015389W/mm^2 at the skirt. This, in turn, is caused by the effect of heat conduction at the top of the piston and heat convection to side lands as indicated in Fig. 6

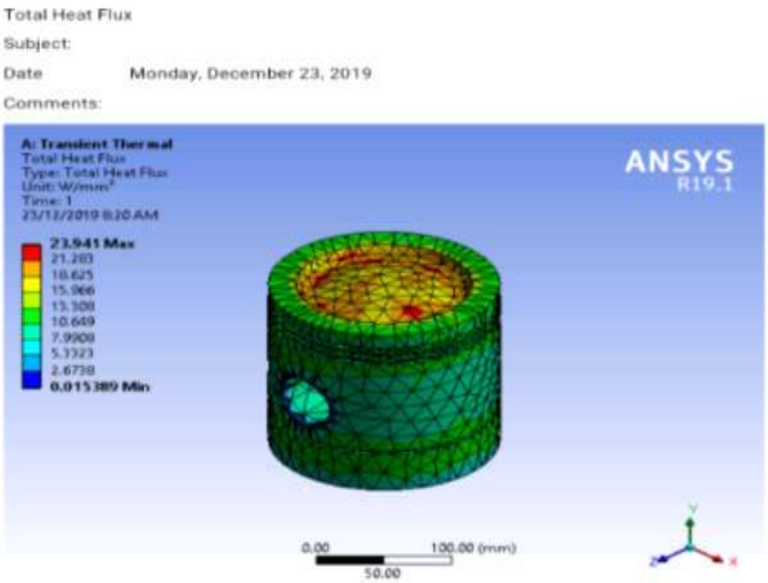

Fig.6: Total heat flux of the MDE piston

D. Directional Heat Flux

The MDE piston experiences a maximum directional heat flux of 14.277W/mm^2 at the piston crown and a minimum directional heat flux of -14.346W/mm^2 at the skirt. This is as a result of heat conduction at the top of the piston and heat convection to side lands as revealed in Fig. 7

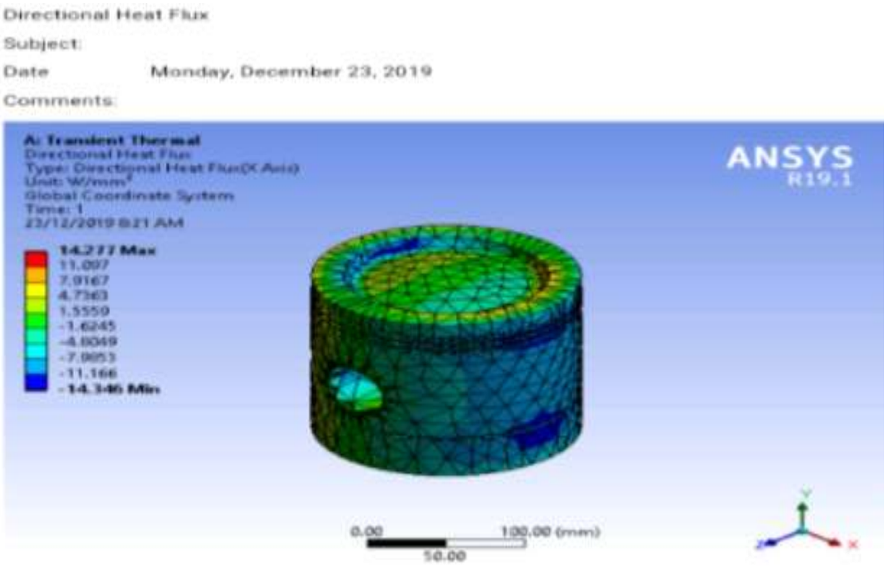

Fig. 7: Directional Heat flux of the MDE piston

E. Temperature

The MDE piston experiences a maximum temperature of 2179.6^{o}C at the piston crown and a minimum temperature of 80.89^{o}C at the skirt. This, in turn, is subjected to the influence of heat conduction at the top of the piston and heat convection to side lands as revealed in Fig. 8.

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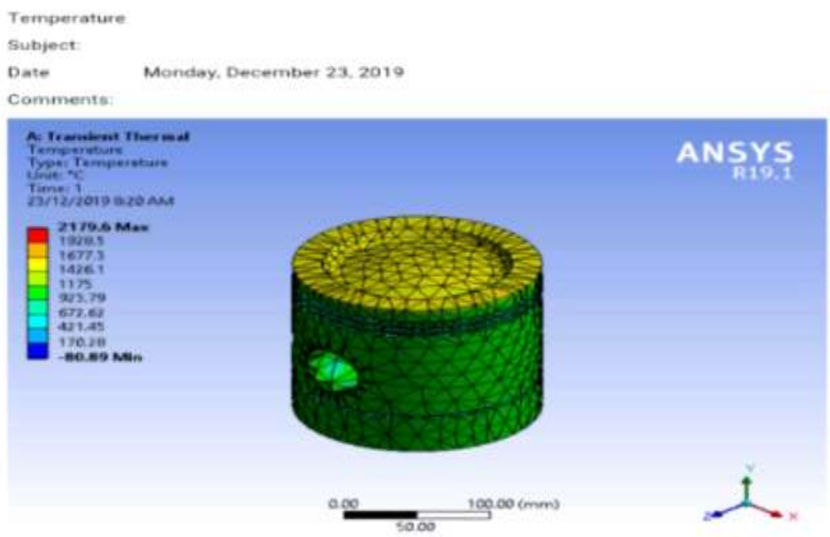

Fig. 8 Temperature of the MDE piston

F. **Equivalent Elastic Strain**

The MDE piston experiences a maximum equivalent elastic strain of 0.03259mm/mm at the piston crown and a minimum equivalent elastic strain of 0.0016228mm/mm at the skirt. This, in turn, is subjected to the influence of heat conduction at the top of the piston and heat convection to side lands as revealed in Fig.9

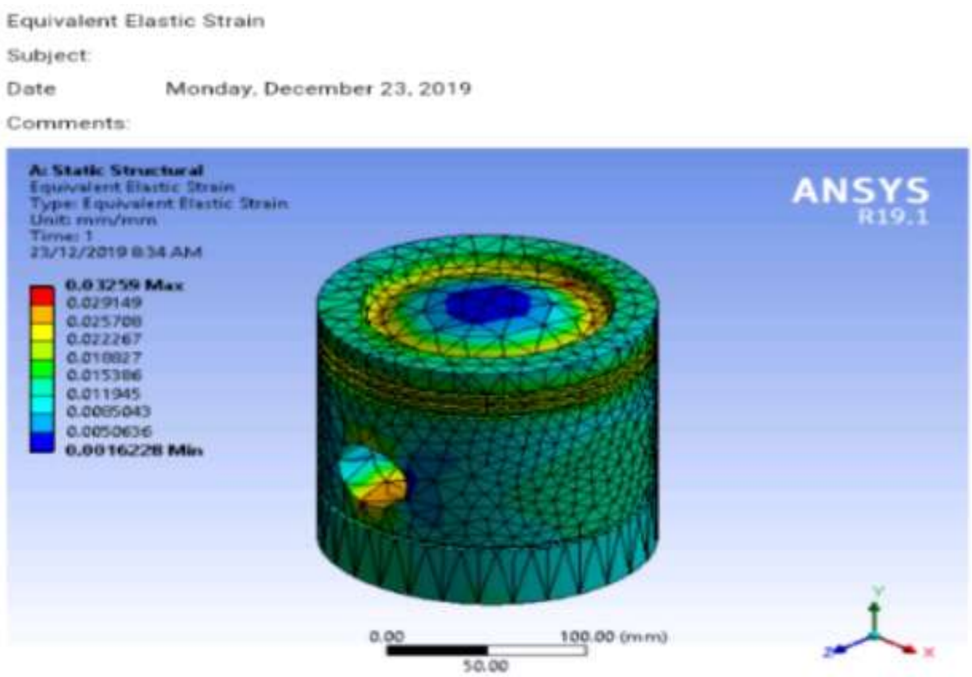

Fig. 9 Equivalent Elastic Strain of the MDE piston

G. **Principal Elastic Strain**

The MDE piston experiences a maximum principal elastic strain of 0.021177mm/mm at the piston crown and a minimum principal elastic strain of 0.0025653mm/mm at the skirt. This, in turn, is subjected to the influence of heat conduction at the top of the piston and heat convection to side lands as revealed in Fig. 10.

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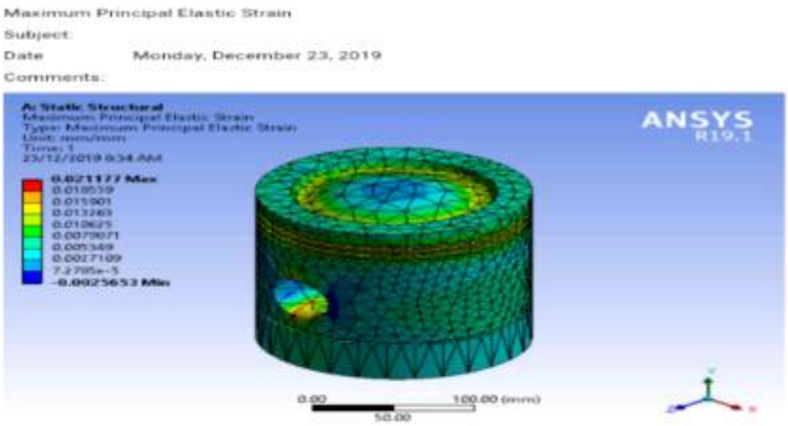

Fig. 10 Principal Elastic strain of the MDE piston

H. Equivalent Stress

The MDE piston experiences a maximum equivalent stress of 6408.6MPa at the piston crown and a minimum equivalent stress of 270.05MPa at the skirt. This, in turn, is subjected to the influence of heat conduction at the top of the piston and heat convection to side lands as revealed in Fig. 11.

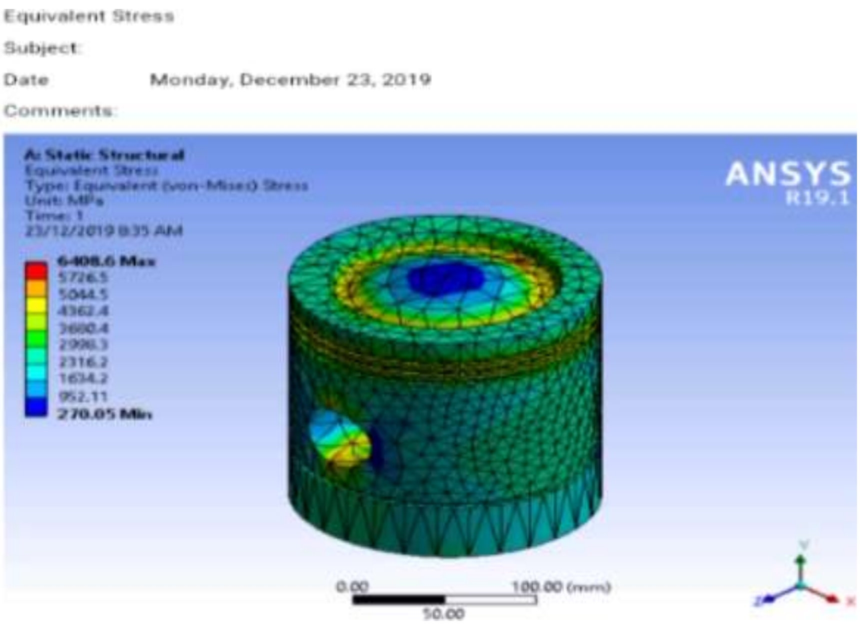

Fig. 11 Equivalent Stress on the MDE piston

I. Optimisation Of Piston

After generating a finite element model using ANSYS software, a strategy for the optimisation workflow is defined. Target of the optimisation is to reach a mass reduction of the piston**.** Therefore, the objective function is to minimize mass, subject to the following constraints:

(i) Allowable or design stress should not exceed the maximum Von-Misses stress
(ii) Manufacturing constraints should not be violated
(iii) Detailed stress-loading analysis on the piston should be carried out to ensure that areas where excess materials are removed do not exceed the allowable maximum von-Misses stress with factor of safety kept at 1.5.

Table 3: Piston Design Parameters after Optimisation(Source: Manufacturer's manual of the MDE onboard MT Otuoke in NPA, Rivers Port)

S/No	Piston Design Parameters (mm)	Before Optimisation	After Optimisation	Design Consideration
1	Radial Thickness of the ring (t_1)	5.24	3.46	4.0
2	Axial thickness of the ring (t_2)	5.0	3.52	4.0
3	Maximum thickness of the barrel (t_3)	14.34	9.08	9.0
4	Width of the top land (b_1)	10.84	9.36	10.0
5	Width of the ring land (b_2)	4.0	3.24	3.0
6	Von-Misses Stress [MPa]	85.6439	55.6685	69.0
7	Deflection	0.051762	0.025884	0.05884

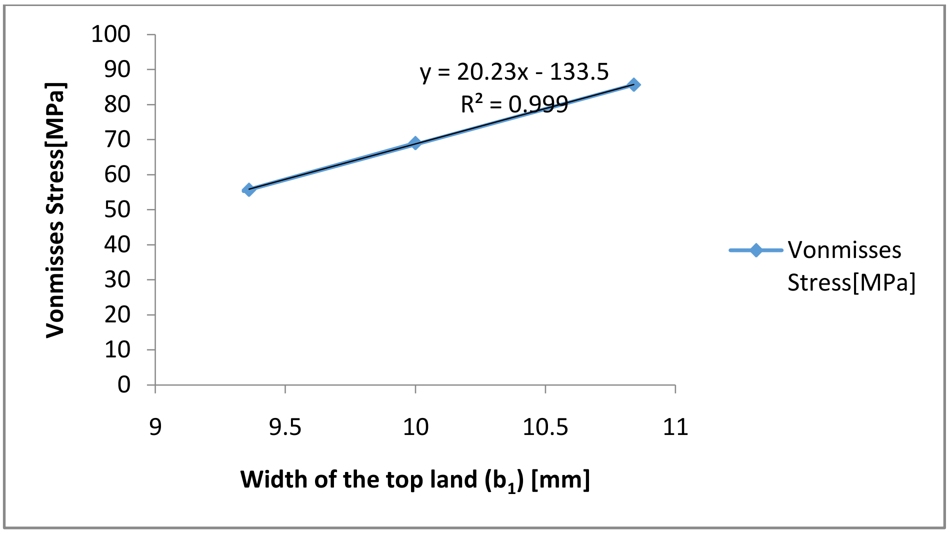

Fig. 12: Von-Misses stress at different width of the piston top land

The Figure12shows that the Von-Misses stress on the MDE piston are 85.6439MPa, 55.6685MPa and 69MPa at the respective piston top-land width of 10.84mm, 9.36mm and 10mm.The width of the top land near piston rings is 5mm in size and is changed due to pressure and heat applied on rings through groves.

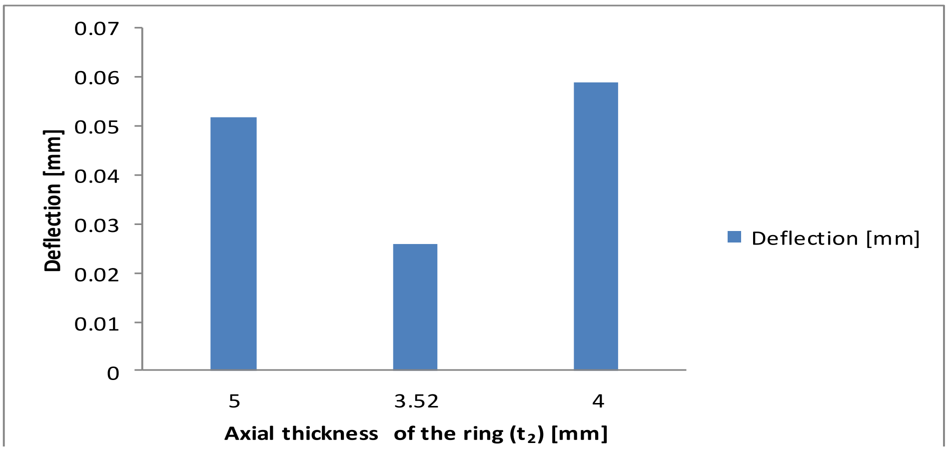

Fig. 13: deflection at different axial thickness of the piston ring

The value after optimisation is 3.52mm and is rounded to 4mm.The figure 13. showed that the deflections on the MDE Piston are 0.051762mm, 0.025884mm and 0.05884mm at the respective piston axial thickness of 5mm, 3.52mm and 4mm.

V. CONCLUSION

Thermal stress done on piston using ANSYS tool with a view to optimizing the performance data. The stress distribution on the piston mainly depends on the deformation of piston. Therefore, in order to reduce the stress concentration, the piston crown should have enough stiffness to reduce the deformation.

This work adds credence to previous works in the area of optimisation and improvement of the design of MDE piston in order to enhance its reliability and robustness. The thermal and geometric properties of MDE piston are investigated against the thermal stress stipulated in the delivery. Hence, conducting a thermal stress analysis, performance optimization of MDE piston and its sealing rings are the motivation for this research. Transmission of mechanical work that contains fluids is the main function required of the MDE piston in the engine cylinder combustion chamber.

Finally, the optimal results reveal that the investigated MDE Piston experiences in a maximum equivalent stress of 6408.6MPa at crown and a minimum equivalent stress of 270.05MPa at skirt. The result of analysis also indicated that the Von-mises stress has changed from 85.6439MPa to 55.6685MPa and the biggest deformation has been reduced from 0.051762mm to 0.025884mm.

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