Coupled Structural and Thermal Analysis of IC Engine Piston Head with Various Shape

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Abstract— The design of engine parts is complex and efficiency is related to the material used. Basic design calculation is to be made for a selected type of carburettor or diesel engine component. This uses standard procedure of obtaining critical dimensional values from empirical formulae and material constants resulted from previous experimental data. A three-dimensional model can be made using solid modelling software's like CATIA and mesh can be generated. Further, a finite element model can be made and analysis can be carried out using software's like ANSYS. With help of this analysis, points where high stresses are observed due to the structure of piston can be studied from the results. For different standard alloys being used in manufacture of pistons to optimization of design values at the early stages by exploring new materials is always an interest to engineers. Also studying different modes of failure caused in piston head, skirt and rings will help in designing in a better way to prevent failure and life of engine member can be precisely told. Considering these advantages, a comparison of three types of piston heads is presented in this work.

Key words: Piston, CATIA, ANSYS, Structural, Thermal

I. Introduction

Structure and working environments of pistons are very complex. In the working environment, the pistons will produce stress and deformation because of the periodic load effect, which are from high gas pressure, high speed reciprocating motion from the inertia force, lateral pressure, friction and so on. Burning of the high-pressure gas produces high temperature, which makes piston move out due to expansion thus its interior produces thermal stress and thermal deformation. The thermal deformation and mechanical deformation will cause piston cracks, tortuosity, etc. Therefore, it is essential to analyse the stress field, temperature field, heat transfer, thermal load and mechanical load coupling of piston, etc. in order to lower the heat load and improve the thermal stress distribution and improve its working reliability during operation. Analysis method of the finite element provides a powerful calculation tool, which is better than test and theory analysis method and has become an important means for internal combustion engine performance study. By analysis of the piston working process, we find that stress and deformation of the piston is most serious under the steady speed conditions when the gas-fired pressure is the maximum. At the same time, the strength of piston has a limit. Therefore, it is essential to choose the piston under the rated power and we only analyse distribution force in the axis of the force, including the maximum explosion pressure and reciprocating inertia force. Pressure load of piston is that gas pressure affects piston top surface due to high pressure in the cylinder. For simplified analysis, we can use the steady state process, but cannot ignore the effect that combustion power stroke produces, i.e. impact load for piston. The piston head or crown receives the majority of the initial pressure and force caused by the combustion process. It is also subjected to thermal expansion caused by the transfer of heat from the head to the body of the piston. When Pistons are operating, they directly touch the high temperature gas and their transient temperature can reach more than 2500K and generates the 18KW power. Piston is heated seriously and its heat transfer coefficient is 167 W/ (m°C) and its heat dissipation coefficient is poor, so the piston temperature can reach 600 ~ 700 K approximately and the temperature distributes unevenly. On the basis of these conditions, we will make thermal analysis for the piston. A tentatively correct method of designing a piston would be to consider the thermal stresses and normal stresses acting on the face of the piston. The method is rudimentary but would provide us a fair approximation as to the nature of durability we need to provide in the material property of the piston. We need to find the force being exerted on the cross-sectional area of the piston by the hot gases.

A. Problem Definition

The piston model has been taken under the performance investigation in that we have planned to change piston head. Analyse the piston heads with material i.e. Aluminium alloy. Compare total deformation, von-misses stress and strain, temperature distribution and heat flux of various piston head models.

B. Objectives

The main objective of the present work is to find out and suggest optimize piston head shape based on quality and economy considering material weight, stress and strain and deformation. After generating an accurate finite element model, a strategy for the optimization of material workflow was defined. Target is to optimizing piston head and material.

II. Analysis Procedure

A. Solid Modelling

In present work, CATIA V5 is used. From the obtained values of dimensions from initial calculations, a two-dimensional sketch of one half in total vertical cross section is made along with a central axis. The sketch is now three dimensionally modelled using the SWEEP function along the central axis. The model is now saved as stp or igs file. The file is now ready to be exported to any other compatible analysis software with minimal disruption in data and surface profiles. Heading to the phase of two-dimensional model, various sketches changing the shapes of dome and dimensional values will result in different models and for each of it further analysis can be made separately.

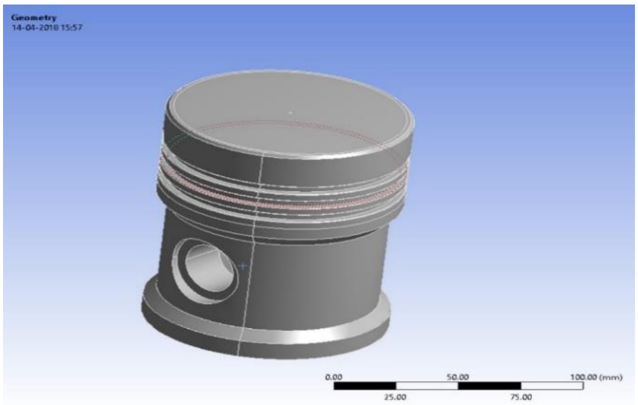

Fig. 1: 3D model of Flat Head Piston

B. Material

The material chosen for the piston is Aluminium Alloy. Its Fatigue properties are presented in table.

Property	Value	Units
Density	2770	Kg/m^3
Tensile Yield Strength	2.8E+8	Pa
Compressive Yield Strength	2.8E+8	Pa
Tensile Ultimate Strength	3.1E+8	Pa
Compressive Ultimate Strength	0	Pa
Young's Modulus	7.1E+10	Pa
Poisson's Ratio	0.33	-

Table 1: Material Properties

C. Meshing

A coarse type relevance centre is chosen and keeping the element size as default by the software, minimum edge length observed is 2.e-003 m. The mesh size is 5 mm.

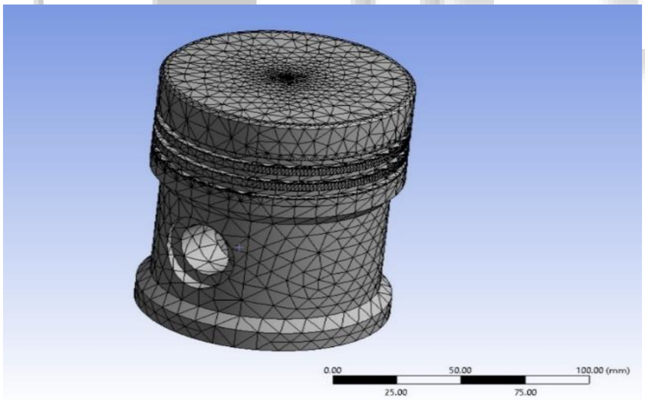

Figure 2. Meshing of Piston

D. Thermal Boundary Condition

Temperature at top of the piston is 700^0 C. The heat dissipation from piston in the form of convection and radiation. The heat flow from piston to surroundings is assumed as convective mode of transfer. The convection boundary conditions along with the temperatures at the piston pin regions are applied on different regions as boundary conditions by calling the related entity sets that were created in individually from the component manager. The solving of the problem was done. The results obtained after the solving can be viewed in the post processing tree. The final results display the distribution of temperatures on the surface of the piston crown.

E. Structural Boundary Condition

In case of thermal stress analysis, all the displacements at the piston pin region set to zero to act as boundary conditions. The pressure apply on the top of the piston is 10 N/mm^2. The temperatures obtained from thermal analysis were also applied on to the piston to get thermal stresses. The boundary conditions applied. In addition to the boundary conditions considered for thermal stress analysis instead of temperature, a pressure was applied on the crown and the inertia force was also applied to get the von-misses stresses.

III. RESULTS AND DISCUSSION

After processing solution, the contours of Von-Mises Stresses, Total Deformation, and Equivalent Elastic Strain in Static structural analysis are plotted. On other had the Temperature and Total Heat Flux in transient thermal analysis. These results as part of structural and thermal analysis are obtained for Cup shaped, Dome shaped and Flat shaped pistons with Aluminium alloy. We are getting three results of each property.

A. Result of Flat Head Piston

A maximum stress on flat head 317.92 to 950 Mpa are observed. Total deformation of 1.152 mm is obtained for the applied pressure which is considerable after many number of cycles of operation. The axial deformation along X and Y directions is maximum at intersection of side wall and head surface of piston. The maximum heat fluxes observed are 2.203 W/mm^2.

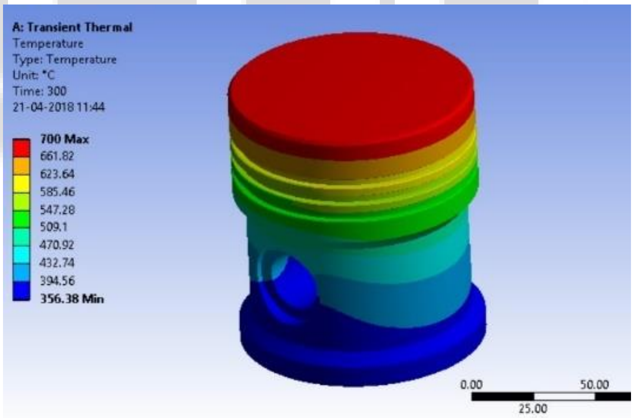

Fig. 3: Temperature distribution of flat head piston

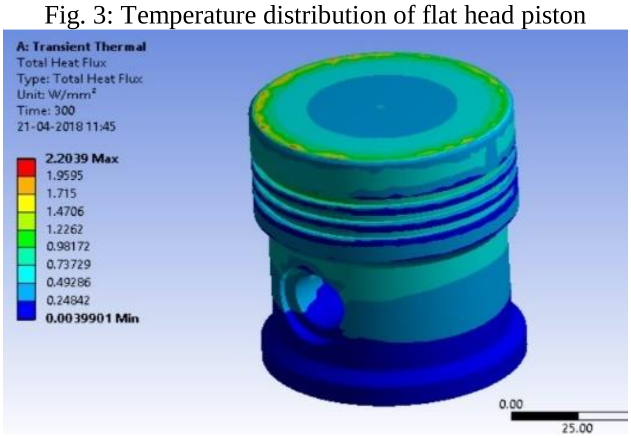

Fig. 4: Total heat flux of flat head piston

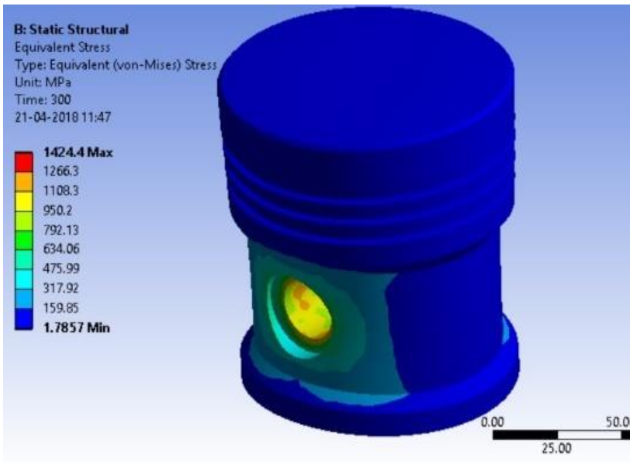

Fig. 5: Von-Mises Stress of Flat Head Piston

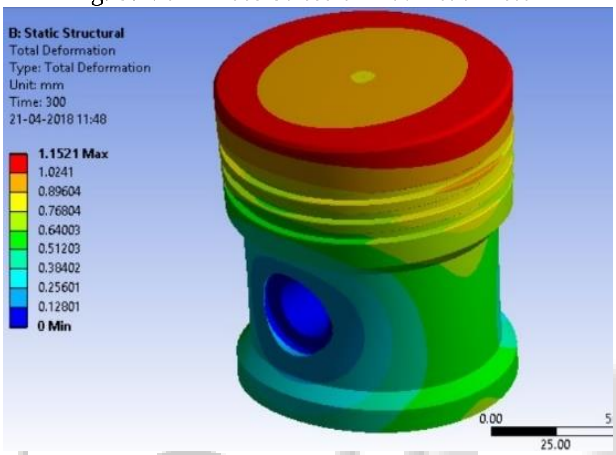

Fig. 6: Total Deformation of Flat Head Piston

B. Result of Cup Head Piston

A maximum stress on cup head 377 to 527 Mpa are observed. Total deformation of 0.491 mm is obtained for the applied pressure which is considerable after many number of cycles of operation. Maximum value of strain i.e. 0.0062 mm/mm is observed at lower surface of cup shape whereas the axial deformation along X and Y directions is maximum at edges of the cup shape. The heat fluxes observed are 0.92 W/mm^2 as maximum.

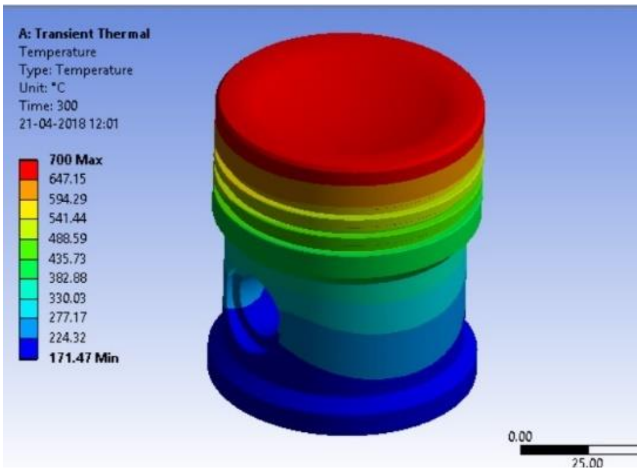

Fig. 7: Temperature distribution of cup head piston

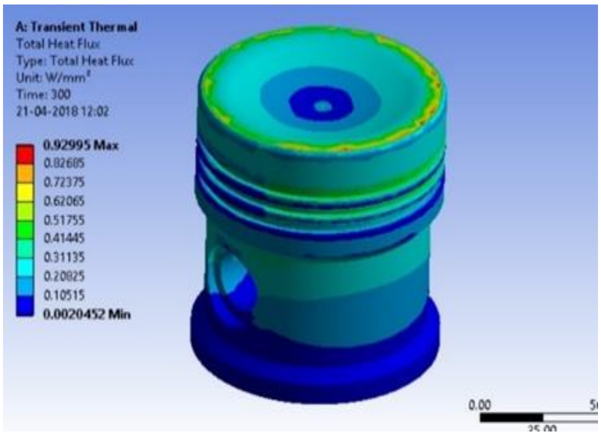

Fig. 8: Total heat flux of flat head piston

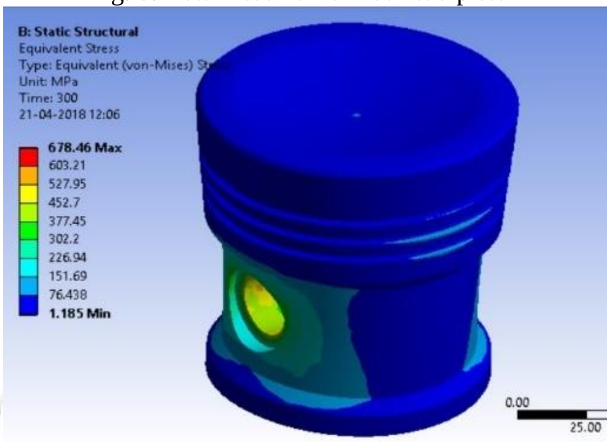

Fig. 9: Von-Mises Stress of Flat Head Piston

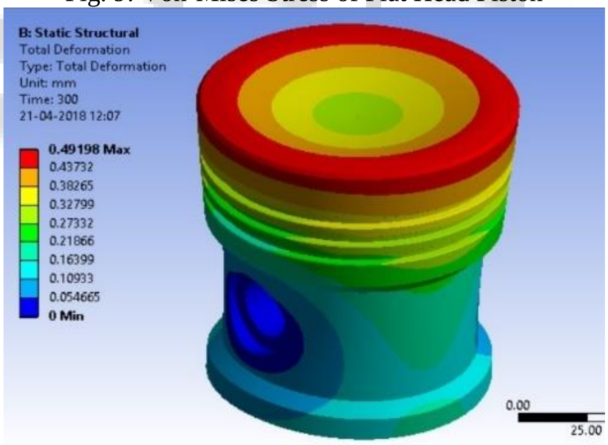

Fig. 10: Total Deformation of Flat Head Piston

C. Result of Dome Head Piston

A maximum stress on dome head 364 to 1268 Mpa are observed. Total deformation of 1.20 mm is obtained for the applied pressure which is considerable after many number of cycles of operation. The axial deformation along X and Y directions is maximum at intersection of side wall and head surface of piston. The maximum heat fluxes observed is 1.683 W/mm^2.

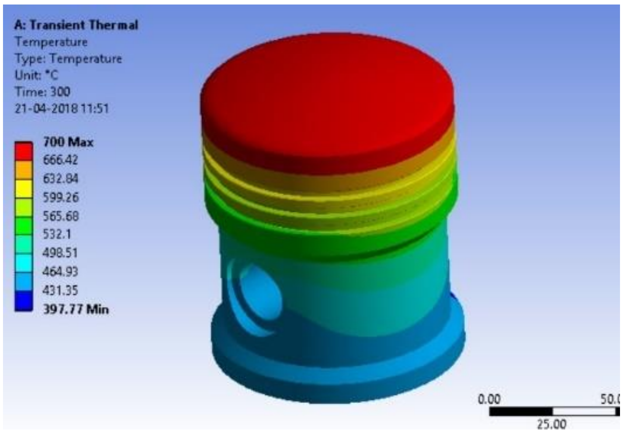

Fig. 11: Temperature distribution of cup head piston

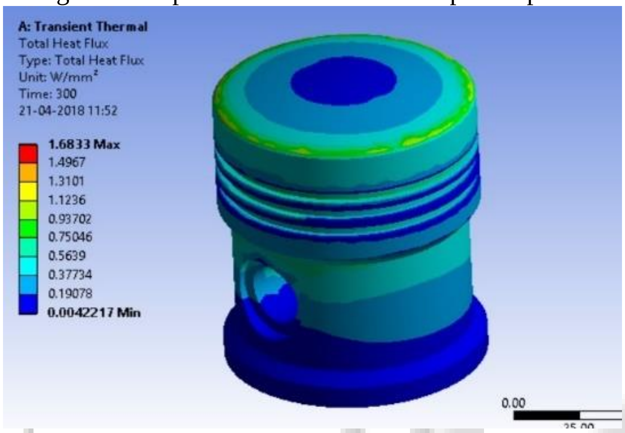

Fig. 12: Total heat flux of flat head piston

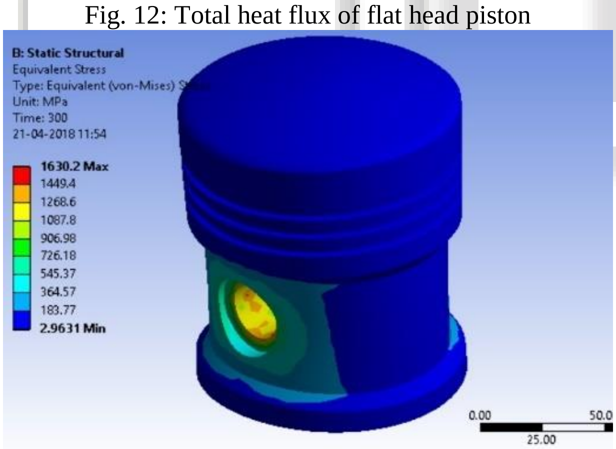

Fig. 13: Von-Mises Stress of Flat Head Piston

D. Result Table

Piston Head	Heat Flux (W/mm^2)	Equivalent Elastic Strain (mm/mm)	Equivalent Von-Mises Stress (Mpa)	Total Deformation (mm)
Flat Head	2.203	0.020	950	1.152
Cup Head	0.929	0.0062	527	0.491
Dome Head	1.68	0.022	1268	1.201

Table 2: Result Table

IV. CONCLUSIONS

In comparison between the three types of piston head for which the analyses are carried out, the stresses and total deformations observed in cup shaped piston are lower than the flat and dome shaped piston. So, this justifies the usage of cup shaped pistons in IC Engines which use diesel as fuel and for large sized engines. Because in those type of engines, the turbulence creation is more important than the structural integrity over time. This is to ensure prevention of knocking and also creating room for complete combustion of fuel. On other hand, the dome shaped pistons can be used for light weight daily motoring vehicles with low maintenance as they incur lower deformation. The heat flux distribution over the cup shape piston shows a least value which implies that not much of heat being transferred to skirt side of piston. This will result in increased life of piston rings and piston pin as they won't get subjected to thermal fatigue. The present work concentrated on comparison of three piston designs with same material which gave a positive result to move forward in optimizing i.e. through design modifications and increasing the complexity.

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