Structural and Thermal Analysis of a C.I. Engine Piston of Different Materials Using FEM Technique

Puran Singh
Research Scholar, FET,
Mechanical Engineering Department,
MRIU, Faridabad, India
E-mail: puran.singh910@gmail.com

Dr. Debashis Pramanik
Professor, FET,
Mechanical Engineering Department,
MRIU, Faridabad, India
E-mail: debashis.fet@mriu.edu.in

Abstract: *Internal combustion engines have been, and will remain for the foreseeable future, a vital and active area of engineering education and research. Most of the researches in internal combustion engines are operating performance and fuel performance oriented. Almost all of the components in an internal combustion engines are subjected to thermal loads. Every mechanical component is designed for a particular structural and thermal strength. Piston seizure and cylinder block melting are typical problems when thermal and structural loads on the components exceeds the design strengths. Piston is a cylindrical component fitted into the cylinder and forms the moving boundary of the combustion system. It fits perfectly into the cylinder providing gas tight space with the help of piston rings and lubricant. These pistons are made of three different types of materials Alloy steel-1040, aluminium alloy-6061 and cast iron. Structural and thermal analysis will be carried out on problem made up of these materials using simulation software ANSYS. The peak surface temperature of the piston material when there is no cooling is about 1980^{o}C against 518 ^{o}C when cooling was provided in an aluminium piston. Peak stress in the piston due to combustion pressure 118 N/mm^2 Typical internal combustion engines leave about 30% of the combustion energy to the cooling water. The boundary conditions are combustion gas temperature of 2000 ^{o}C [3] with a convection heat transfer coefficient of 1500W/m^{2}K. This FEM study can be extended to engine valves, heads, bearing analysis, and fuel injection systems etc.*

Key Words: *Piston, thermal load, structural load, combustion.*

I. INTRODUCTION

Diesel engine is a high mass burning engine. Diesel engine has been the prime mover for all commercial purposes for so long. The compression ratio of a diesel engine is from 16 and 20 [1]. Peak combustion pressures in typical diesel engines are 120, 110, 100, 90, and 80 bars depending upon the motive power needed and the field of application. Typical diesel engine peak combustion temperatures are 3000^{o}C, 2800^{o}C, 2500^{o}C, 2000^{o}C, and 1800^{o}C depending upon the field of applications. Pistons are normally made of alloy steels or cast iron or aluminum because piston material should be a good heat transporter and light in weight, which are the prime requirements of a typical internal combustion engine. Aluminum (alloy 1100) is used as a piston material because it is a good heat transporter (high thermal conductivity k =222 W/m K) and one of the less dense material. We will do FEA of the piston to check if.

1. Piston takes the structural stress induced due to the gas loads.
2. Piston material takes the thermal load.
3. If geometry of the piston is optimized enough to take these loads.

Fig. 1: Typical Diesel Engine Pistons

II. SIMULATION OF PHYSICAL PROBLEM

A. Physical Problem- Structural Load

In the problem under consideration, the combustion pressure is acting on the crown of the piston while it is supported by the connecting rod with the help of piston pin. Though piston is not rigidly fixed, the connecting rod provides necessary support to the piston and takes the gas load.

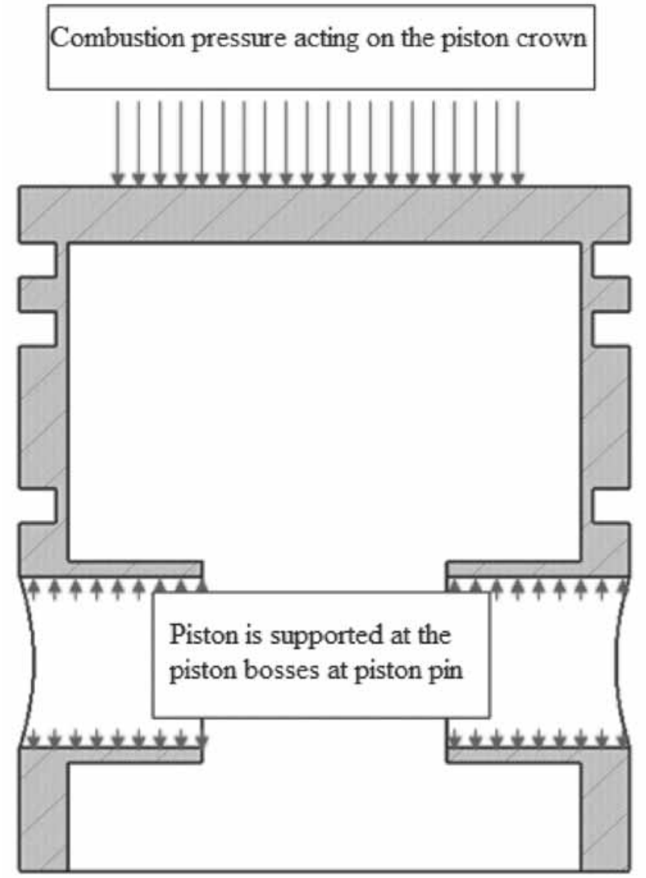

Fig. 2: Statement of the Physical Problem-Structural Load

B. Physical Problem- Thermal Load

Thermal boundary conditions are heat energy (gas at very high temperature with high heat transfer co-efficient) released when fuel is burned and convection cooling loads as shown in Fig. 2. The combustion gas is at a temperature of 2000^{o}C [16] with a with a convection heat transfer coefficient of 1500W/m^{2}K.

III. PROPERTIES OF MATERIALS

Materials properties of the piston material such as [5]

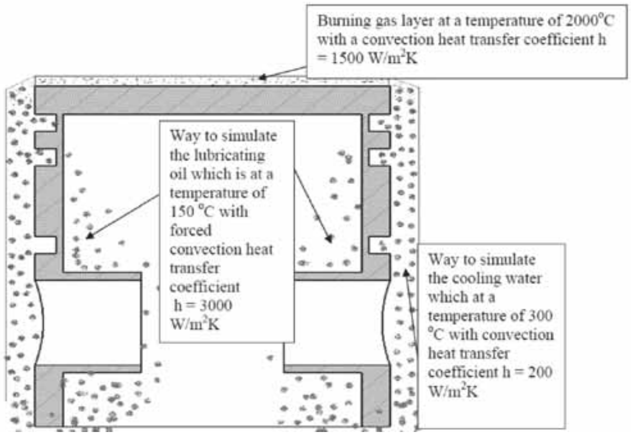

Fig. 3: Statement of the Physical Problem-Thermal Load

Table 1: Materials properties

Sr. No.	Materials properties of the piston
1	Young's modulus of alloy steel -1040 (E = 207 GPa)
2	Young's modulus of aluminium alloy -6061 (E = 69 GPa)
3	Young's modulus of cast iron Grade 80-55-06 (E = 168 GPa)
4	Poisson's ratio of steel material (μ=0.3)
5	Poisson's ratio of cast iron material (μ= 0.26)
6	Poisson's ratio of aluminum material (μ=0.32)
7	Thermal conductivity of the alloy steel (k = 52 W/mK)
8	Thermal conductivity of the cast iron (k = 46 W/mK)
9	Thermal conductivity of the aluminum (k = 180 W/mK)
10	Yield strength of the alloy steel (1040) S =375 N/m^{2}
11	Yield strength of the aluminium alloy (6061) S =276 N/m^{2}
12	Yield Strength of the cast iron(80-55-06) S =379 N/m^{2}

IV. APPROACH FOR ANALYSIS

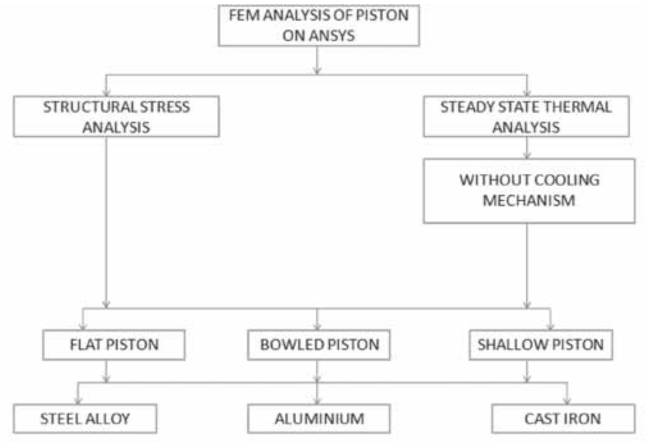

Fig. 4: Approach of the Analysis

V. GEOMETRY CREATION AND MESHING

Table 2: Dimensions of Piston

Part of piston	Size (mm)
Length of piston(L)	152
Outside diameter of piston(D)	140
Radial thickness of ring	5.24
Axial thickness of ring	5
Width of top land	10.84
Width of other ring lands	4

The created solid model was brought in to the ANSYS analysis environment using ANSYS-CREO interface. Piston has so many features like piston pin bosses, and ring grooves. Solid model will have to be turned into to FEM model by dividing the solid model into number of small elements.

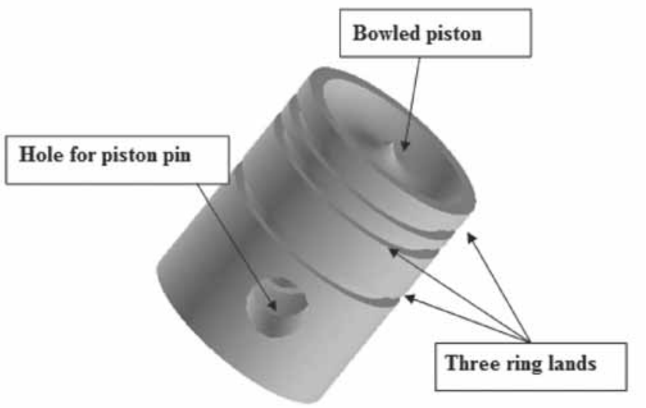

Fig. 5: Bowled Piston

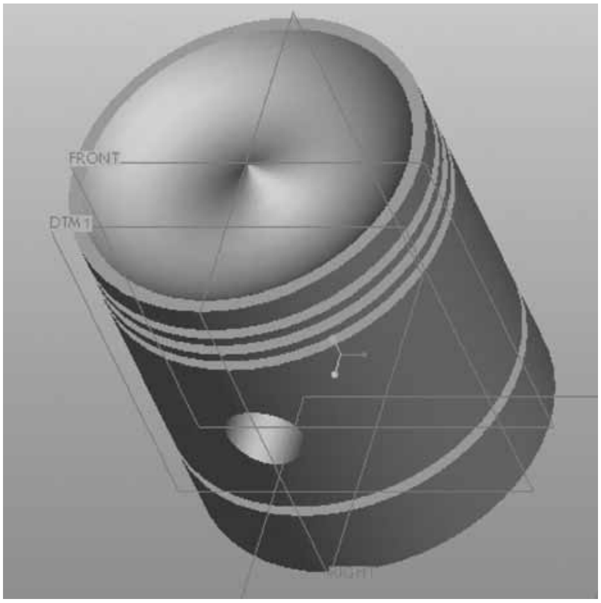

Fig. 6: Flat Shape

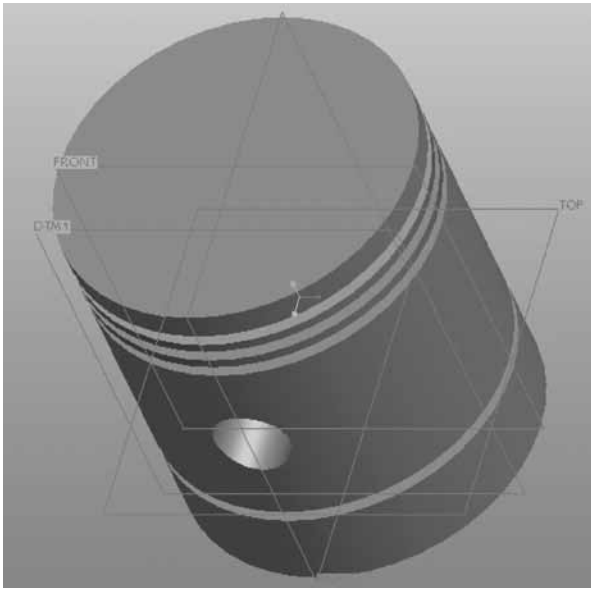

Fig. 7: Shallow Piston

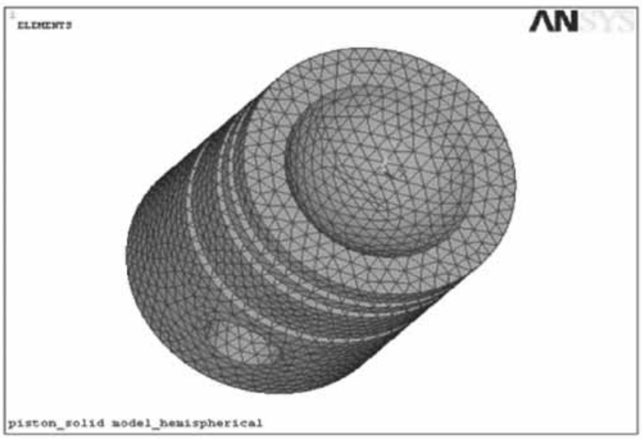

Fig. 8: Meshed Model of the Piston

In simple terms meshing means that connecting the elements with each other. An element is the building block of the finite element model. So the type of element (linear element or higher order elements), number of nodes and their capabilities are important parameters for selecting the elements for a particular analysis. Meshed model of the piston is shown below.

In Number of elements=773409, the element used was Tet 10 node3 SOLID 187 [14] which is a solid element with all six degrees of freedom (translation in all X, Y, and Z and rotations about all three axes); it also has stress stiffening and buckling capabilities. This element is shown below.

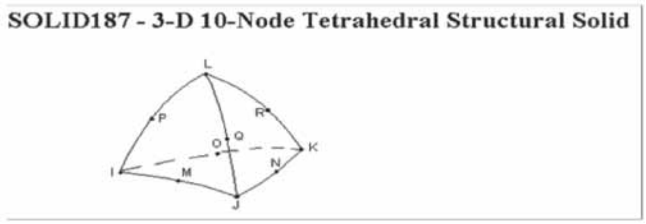

Fig. 9: Element name - Tet 10 node SOLID 187

VI. RESULTS AND THEIR PHYSICAL INTER-PRETATION

Physical Boundary Conditions

After applying the boundary conditions, the problem was solved by the ANSYS Solver. ANSYS solver formulates the governing structural stress strain equations for every element which were solved for the deformations from which all the other quantities such stresses, strains etc can be calculated.

Global conductance matrix for the entire system: $[K]=[T]^T[K]V$

It is a 12*12 matrix where V is volume of tetrahedron element

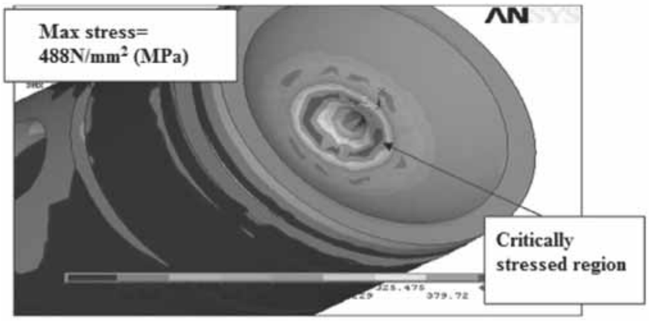

Fig. 10: Von-misses Stress Contour of Bowled Piston when Combustion Pressure =120 bars is Applied.

A. Structural Loading without cooling

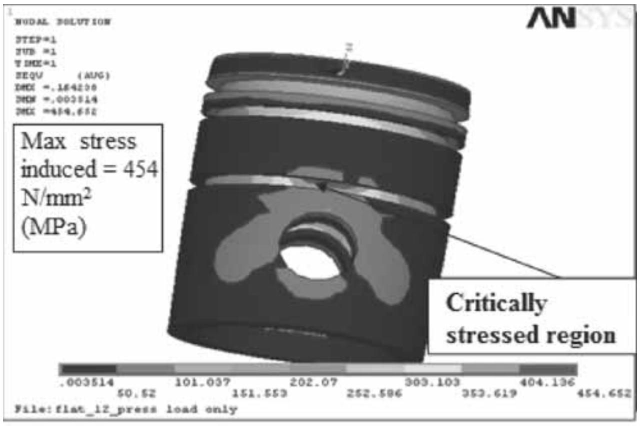

Fig. 11: Von-misses Stress Contour of Flat Piston when Combustion Pressure =120 bars is Applied.

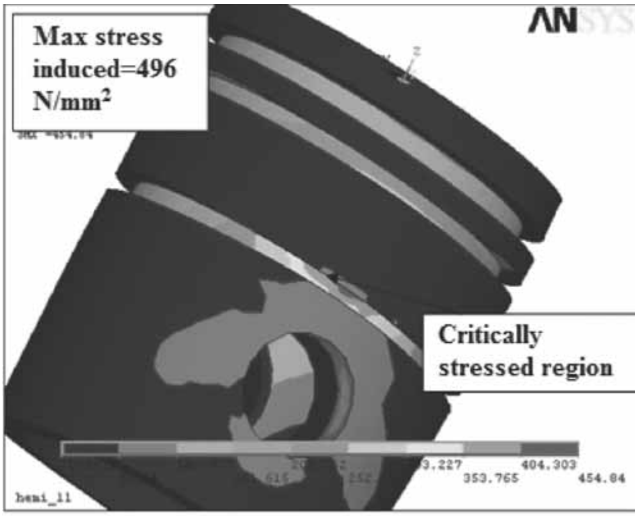

Fig. 12: Von-misses Stress Contour of Shallow Piston when Combustion Pressure =120 bars is Applied.

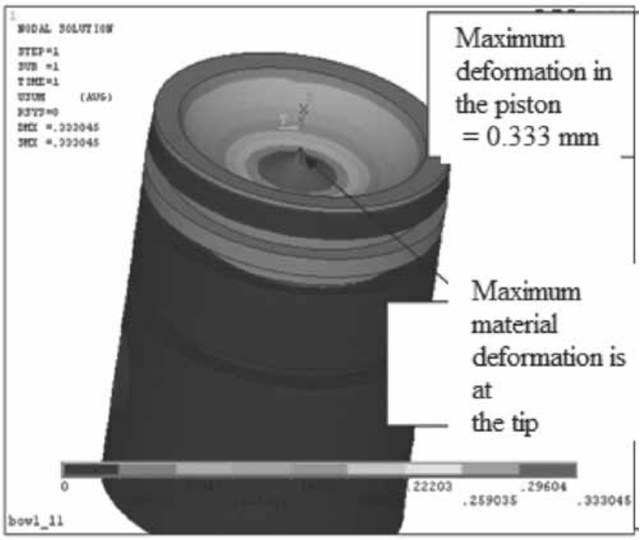

Fig. 13: Deformation Profile of the Piston when Applied Peak Combustion Pressure = 110 bars on a Bowled Piston

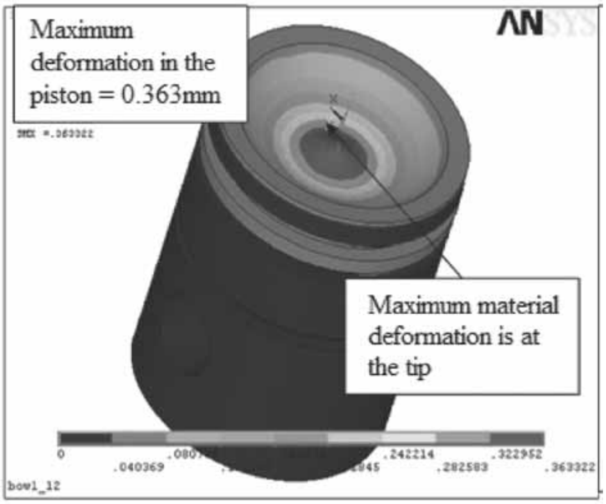

Fig. 14: Deformation Profile of the Piston when Applied Peak Combustion Pressure = 120 bars on a Bowled Piston

Since tip portion of the bowled piston is severely stressed, deformation is also more on that region. The red color indicates the critically deformed regions. The maximum deformation in the material is 0.333, 0.362 for the corresponding pressures of 110,120 bars respectively. As we increase the pressure, deformation also increases.

B. Thermal Loading Without Cooling

Piston has to retain sufficient amount of heat in order to maintain the high thermal efficiency and effective energy conversion. Virtually speaking there is no limit on the surface temperature of the piston but the physically there is a restriction on the maximum temperature that piston surface can have. This restriction is mainly because of the fact that every engineering material will melt when the temperature reaches above the melting point of the material. Thermal boundary conditions are heat energy (gas at very high temperature with high heat transfer co-efficient) released when fuel is burned and convection cooling loads as shown in the following figures below.

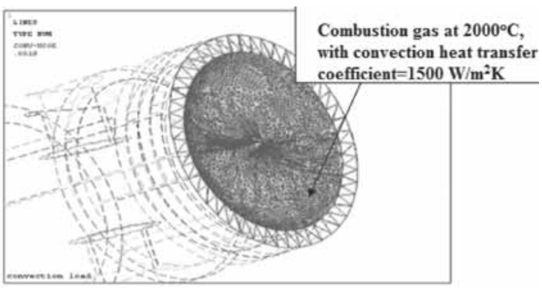

Fig. 15: Thermal Boundary Condition on the Piston with no Cooling Mechanisms [4.6].

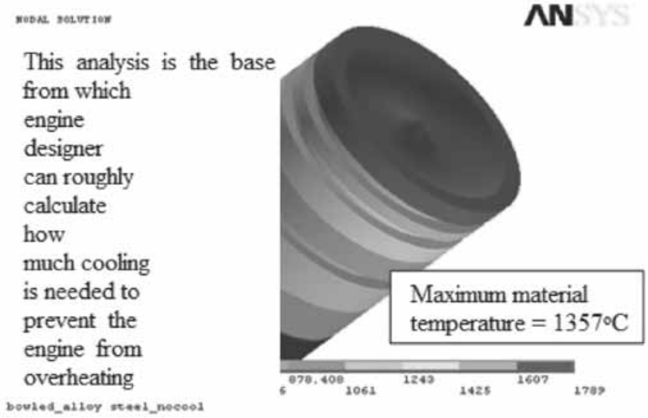

Fig. 16: Temperature Distributions of the Piston made up of Alloy Steel with no Cooling Mechanisms in Bowled Piston Geometry

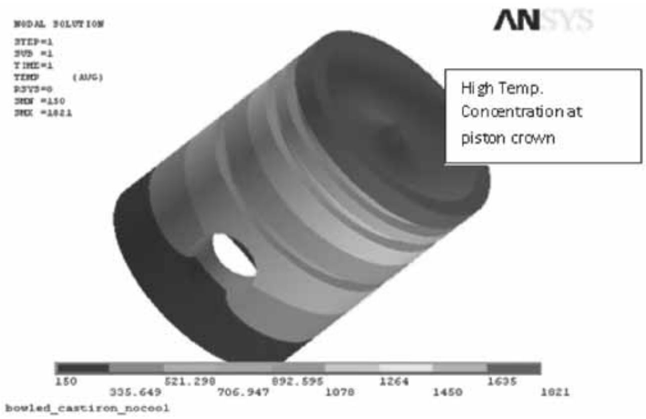

Fig. 17: Temperature Distributions of the Piston made up of Cast Iron in Bowled Piston Geometry.

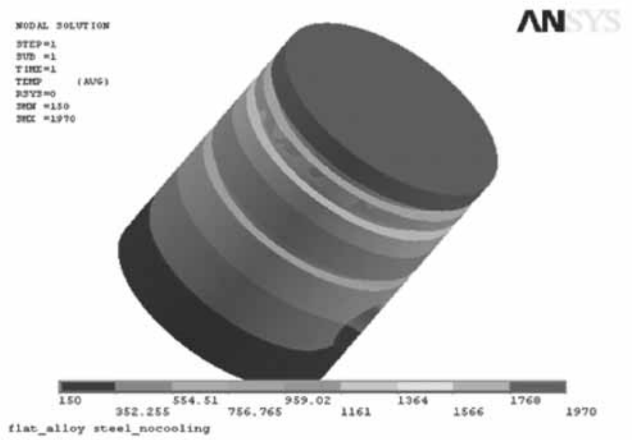

Fig. 18: Temperature Distributions of the Piston made up of Aluminium in Bowled Piston Geometry.

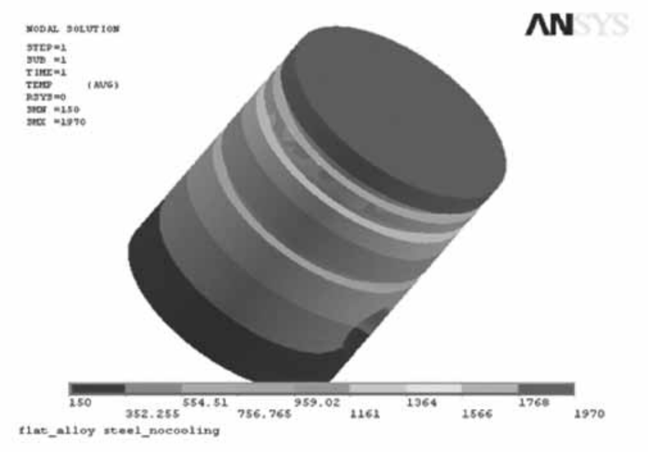

Fig. 19: Temperature Distributions of the Piston made up of Alloy Steel in Flat Piston Geometry.

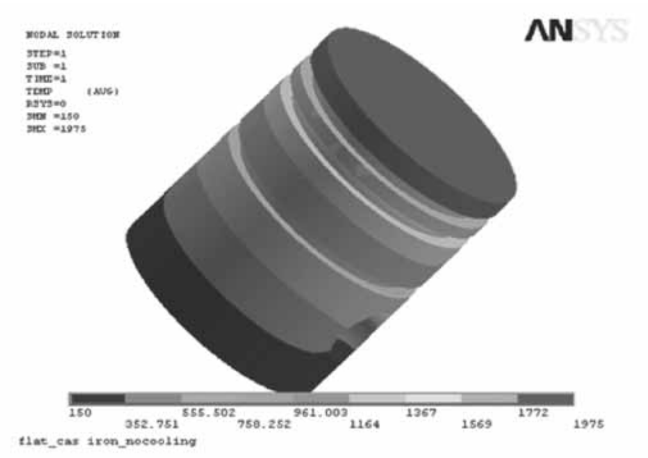

Fig. 20: Temperature Distributions of the Piston made up of Cast Iron in Flat Piston Geometry

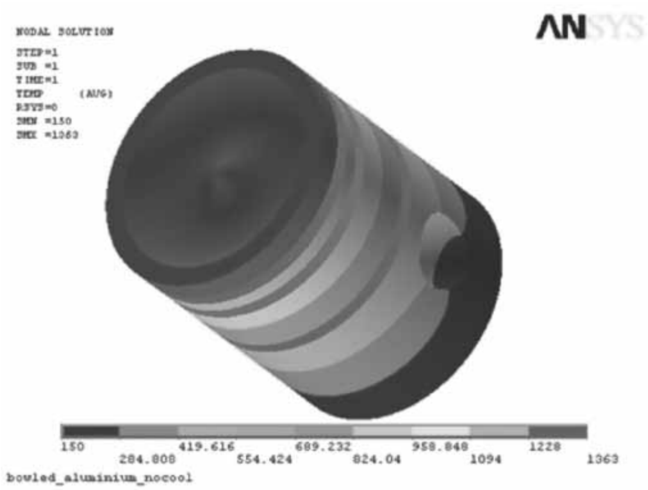

Fig. 21: Temperature Distributions of the Piston made up of Aluminium in Flat Piston Geometry.

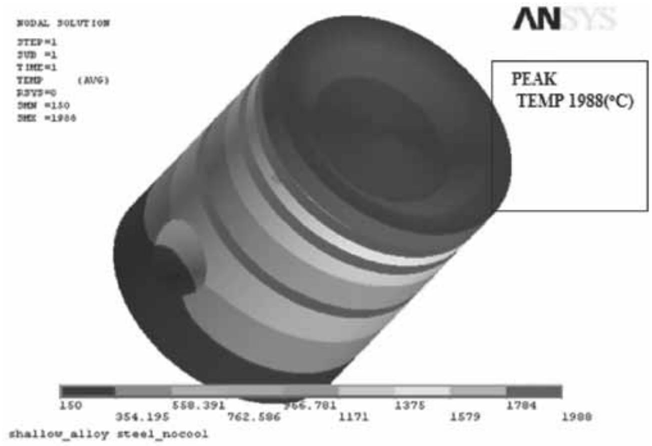

Fig. 22: Temperature Distributions of the Piston made up of Alloy Steel in Shallow Piston Geometry.

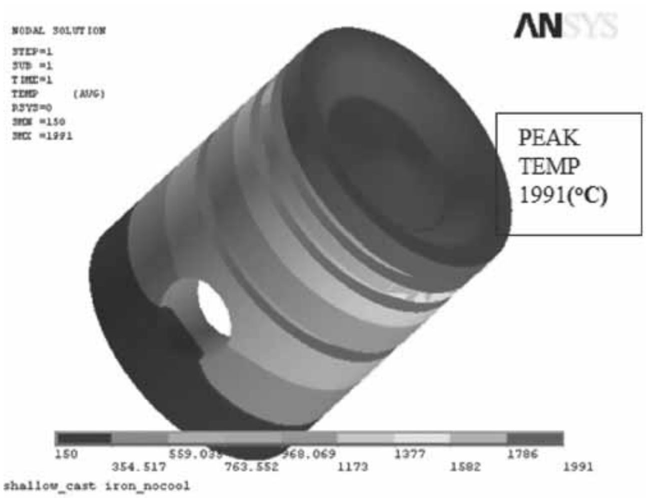

Fig. 23: Temperature Distributions of the Piston made up of Cast Iron in Shallow Piston Geometry

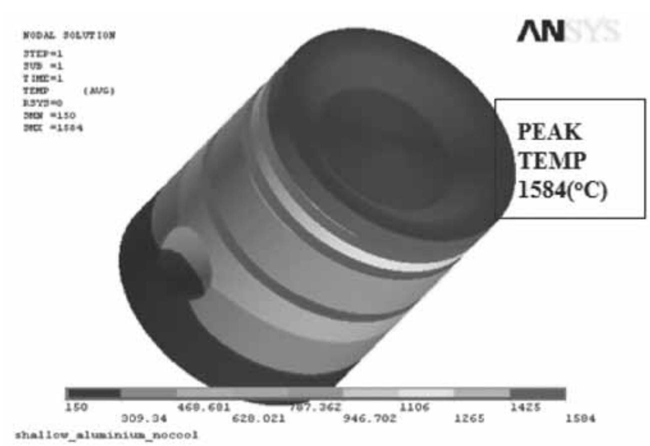

Fig. 24: Temperature Distributions of the Piston made up of Aluminium in Shallow Piston Geometry.

VII. MAXIMUM TEMPERATURE REACHED IN DIFFERENT PISTON GEOMETRY AND FOR DIFFERENT MATERIAL IS SUMMARIZED BELOW

Table 3.1 Summary of thermal analysis with no cooling mechanisms simulated

Shape	Material	Thermal Conductivity (W/mK)	Peak Temp (^oC)
Flat	Alloy Steel	52	1460
Flat	Cast iron	46	1975
Flat	Aluminium	220	1970
Bowled	Alloy Steel	52	1789
Bowled	Cast iron	46	1821
Bowled	Aluminium	220	1363
Shallow	Alloy Steel	52	1988
Shallow	Cast iron	46	1991
Shallow	Aluminium	220	1584

VIII. COMPARISON OF BOTH (WITH AND WITHOUT COOLING) THE THERMAL ANALYSIS

As can be seen from the above temperature plots, By having cooling mechanisms simulated, temperatures were brought down to very low value in most of the regions. This is because of the fact that heat accumulated at the centre need to travel a long distance to dissipate the heat. Here is the summary of material temperatures for the different analysis that were carried out

Table 4: Comparison of both (with and without Cooling) the Thermal Analysis

Shape of the piston crown	piston material	Thermal conductivity (k) in W/mK	Peak material temperature without cooling in ^oC	Peak material temperature with cooling in ^oC
Flat	Alloy steel	52	1460	707
Flat	Cast iron	46	1975	718
Flat	Aluminium	220	1970	518
Bowled	Alloy steel	52	1789	724
Bowled	Cast iron	46	1821	734
Bowled	Aluminium	220	1363	573
Shallow	Alloy steel	52	1988	703
Shallow	Cast iron	46	1991	709
Shallow	Aluminium	220	1584	568

IX. CONCLUSION

The currant study emphasis on stress, deformation, temperature and pressure distributions in the component materials. The study was carried out using the Finite Element Methods Approach. The type of study is peak moment simulation which means that only the conditions prevailing at the point of combustion are simulated. Structural analysis is used to determine deformations, stresses, and reaction forces. Thermal analysis is used to determine the temperature distribution in an object. Other quantities of interest include amount of heat lost or gained. The peak surface temperature of the piston material when there is no cooling is about 1970^oC against 518 ^oC when cooling was provided in a aluminium piston.

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