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Original Research Article

Structural and Thermal Analysis of Different Piston Materials with Cooling (Due to Combustion Pressure) Using Finite Element Analysis

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Abstract

In this research, we will be taking three different types of IC engines piston namely flat, bowled and shallow. These pistons will be made up of three different types of materials Alloy steel-1040, aluminium alloy-6061 and cast iron. Structural analysis will be carried out on all these three designs made up of these different materials to see if they can take the gas load on simulation software ANSYS. After that, thermal simulation of the piston will be done with cooling to see that feasibility of the piston to conduct necessary amount of heat on simulation software ANSYS. Then we will compare the result of structural and thermal analysis and decide the best design and also optimize the final design. By having cooling mechanisms simulated, temperatures were brought down to very low value in most of the regions .Now that most of the regions in the piston are in controlled temperatures. Therefore it is necessary to have dedicated cooling mechanisms for piston without which material melting may not be a surprise. It is also interesting to note that more heat is always concentrated at the center of the piston. This is so in all piston geometries. 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. Analysis carried out was basically a peak moment simulation, in which conditions prevailing at the point of combustion were simulated. Structural load is gas pressure and thermal load is heat energy released by the burning fuel and convection water and oil cooling. The peak surface temperature of the piston material when there is no cooling is about 1980ºC against 518 ºC when cooling was provided.

Key Words: Piston, Structural Analysis, Thermal simulation, Gas load, FEA etc.

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1. Introduction

Pistons are normally made up 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 piston. 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. But it is structurally weak when compared to other materials. So to select the best design and material for the piston we will be taking three different piston designs with three different materials Alloy steel-1040, Aluminium alloy-6061 and Cast iron. We will do FEA analysis of the piston to check if:

1.1.1 Piston takes the structural stress induced due to gas load.

1.1.2 Piston material takes the heat load.

1.1.3 If geometry of the piston is optimized enough to take these loads.

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 the petrol engine is between 6 and 10 while for a diesel engine it 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.

Figure 1.1 Typical diesel engine pistons

2. Simulation of Physical Problem

2.1 Physical problem- structural load

The physical problem is that combustion pressure is acting on the crown of the piston while is supported by the connecting rod with the help of piston pin at the piston pin bosses. Though piston is not rigidly fixed, connecting rod provides necessary support to the piston take the gas load.

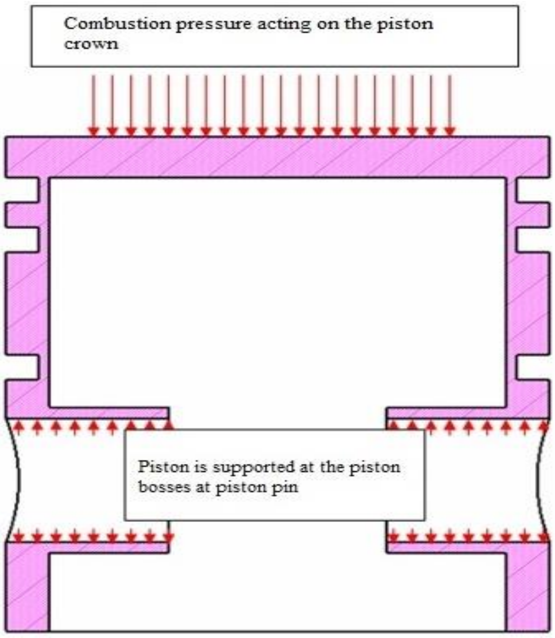

Figure 2.1.1 Statement of the physical problem-structural load

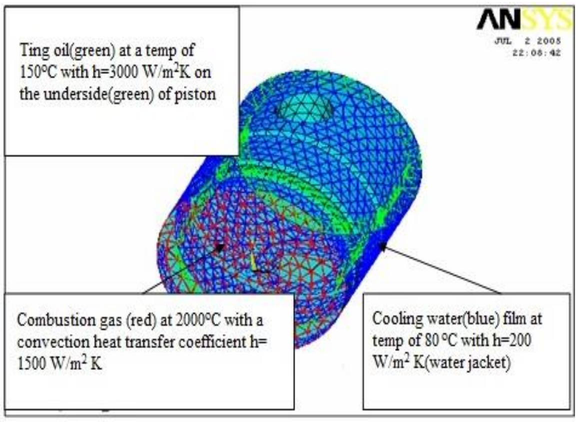

Figure 2.2.1 Thermal Loading with Cooling

2.2 Physical problem-thermal load

In this third stage of the thermal analysis, cooling mechanisms were simulated in addition to the combustion heat load. The boundary conditions are combustion gas is at a temperature of 2000 ^{o}C with a convection heat transfer coefficient of 1500W/m^{2}K and cooling loads are water film with a bulk temperature of 80° C with a convection heat transfer coefficient h = 200 W/m^2 K [16, 7, 17,14]. The other cooling mechanism is lubricating oil at a temperature of 150 ° C with a convection heat transfer co-efficient h = 3000 W/m^2K.

3.1 Approach for analysis

Although piston needs coupled structural-thermal analysis in order to predict the thermal stresses in the engine block, in the current study both the analysis were treated separately because of the fact that engine block is not rigidly fixed and also fact that thermal stresses are very minimum compared to the compressive stress.

Therefore following approach was used to carry out the analysis.

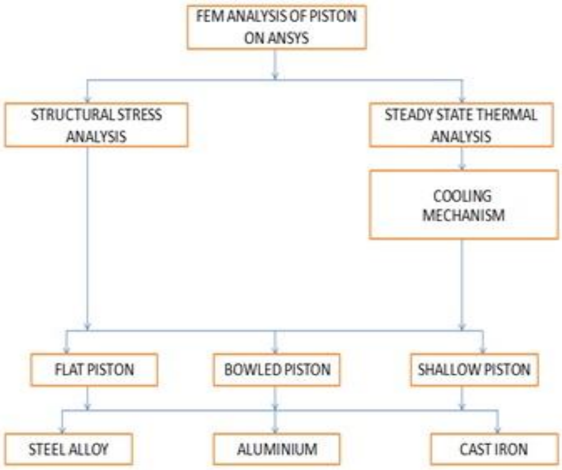

Figure 3.1 Approach of the analysis

4.1 Properties of Materials

Table 4.1.1: Dimensions of piston

SN	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	Thermal conductivity of the alloy steel (k = 52 W/mK)
6	Thermal conductivity of the cast iron (k = 46 W/mK)
7	Thermal conductivity of the aluminum (k = 180 W/mK)
8	Yield strength of the alloy steel (1040) S =375 N/m^2
9	Yield strength of the aluminium alloy (6061) S =276 N/m^2
10	Strength of the cast iron(80-55-06) S =379 N/m^2

5.1 Geometry creation and meshing

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 small elements. This process is called "discritization". Discritization is the process of dividing the solid model into finite number of elements. After dividing the solid model into finite number of elements, they have to be connected to each other as the solid volume is continuous and physically connected at each and every material point.

5.1.1 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

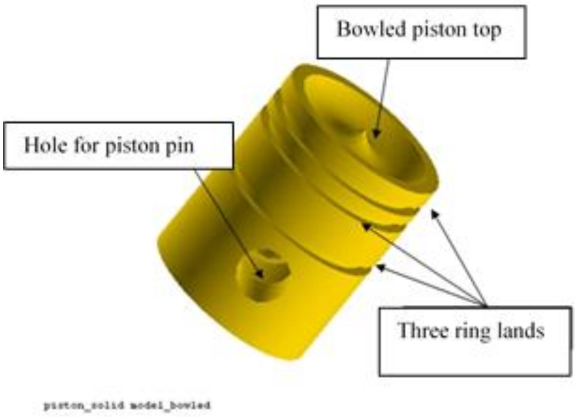

Fig. 5.2 Bowled Shape

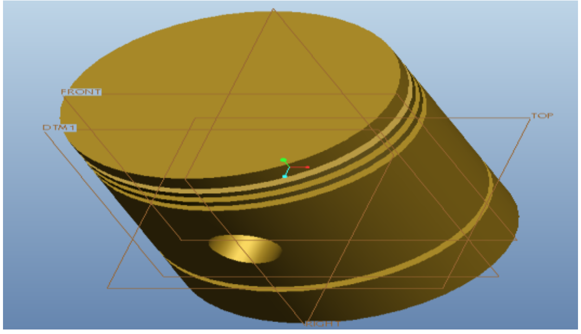

Fig 5.3 Flat Shape

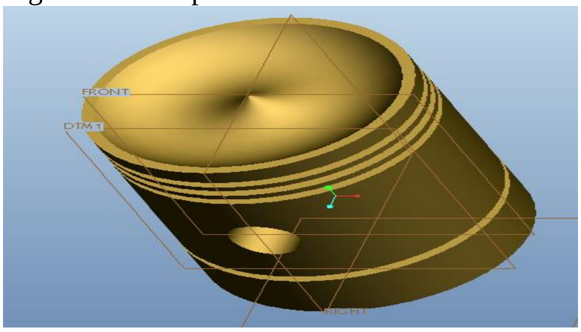

Fig. 5.4 shallow Shape

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 this analysis, the element used was Tet 10 node3 SOLID 187 [14] which is a solid element which has 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:

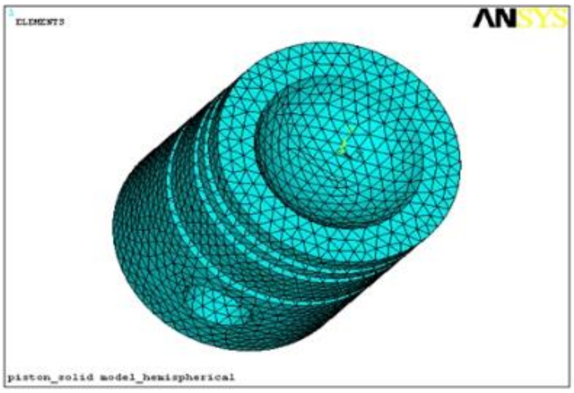

Fig: 5.5 Meshed model of the piston

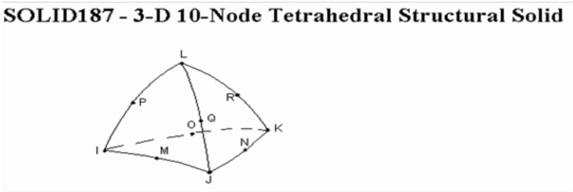

Figure 5.1.5 Element name - Tet 10 node SOLID 187

6.1 Results and their physical interpretation

6.1.1 Physical boundary conditions

Structural loading simply means that applying gas pressure loads the combustion gas pressure was applied on the crown (top surface) of the piston and it is constrained at the piston pin bosses. The gas pressures taken for the study was 120,110, and 100 bars.

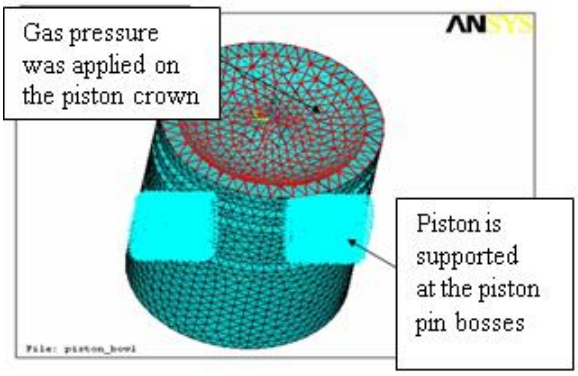

Figure 6.1 Structural boundary condition of the piston when burning is taking place

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

6.2 Structural loading

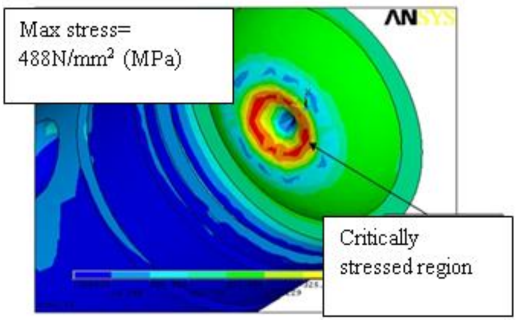

Fig: 6.2.2 Von-misses stress contour of bowled piston when combustion pressure =120 bars is applied

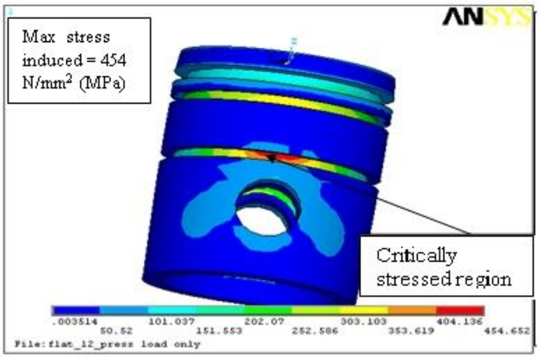

Figure 6.2.2 Von-misses stress contour of flat piston when combustion pressure =120 bars is applied

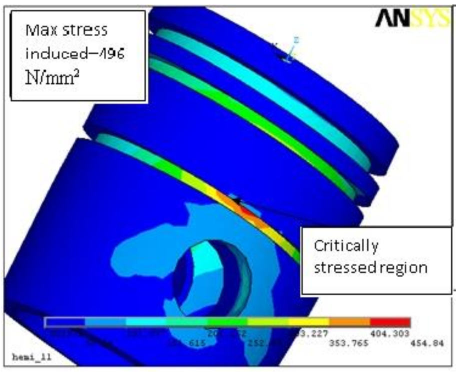

Figure 6.2.3 Von-misses stress contour of shallow piston when combustion pressure =120 bars is applied

6.3 Thermal Loading

The boundary conditions are temperature of 2000^{o}C with convections heat transfer coefficient of 2000^{o}C and cooling by water with bulk temp of 80^{o}C and convection coefficient of h= 200W/m^{2}K [16, 7, 15, 17]. The other cooling mechanism is lubricating oil at 150^{o}C with convection coefficient of h=3000 W/m^{2}K.

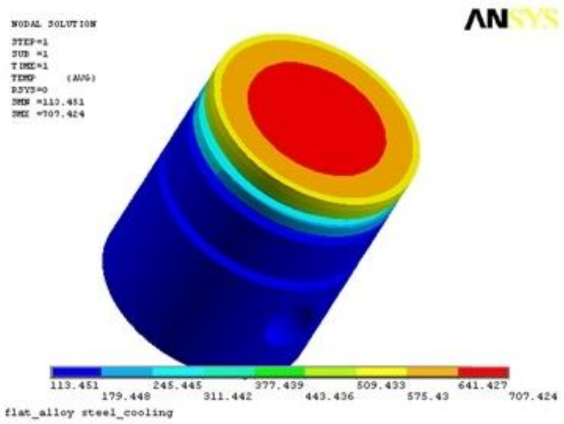

Figure 6.3.1 Temperature distributions of the piston made up of **alloy steel** in flat piston geometry

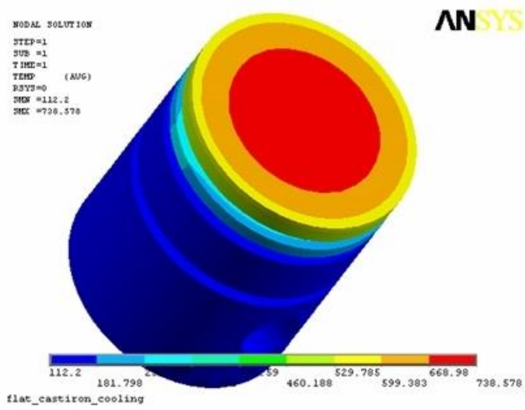

Figure 6.3.2 Temperature distributions of the piston made up of **cast iron** in flat piston geometry

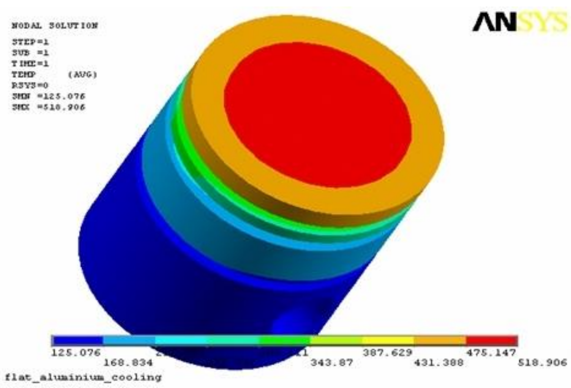

Figure 6.3.3 Temperature distributions of the piston made up of **aluminium** in flat piston geometry

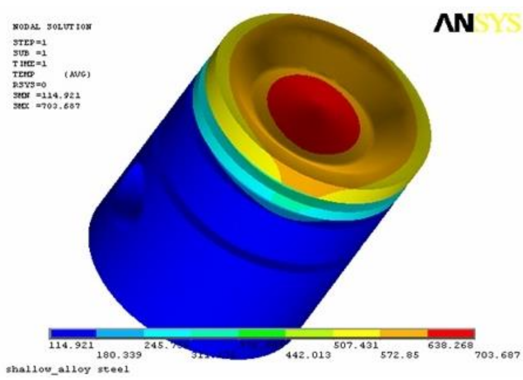

Figure 6.3.4 Temperature distributions of the piston made up of **alloy steel** in bowled piston geometry

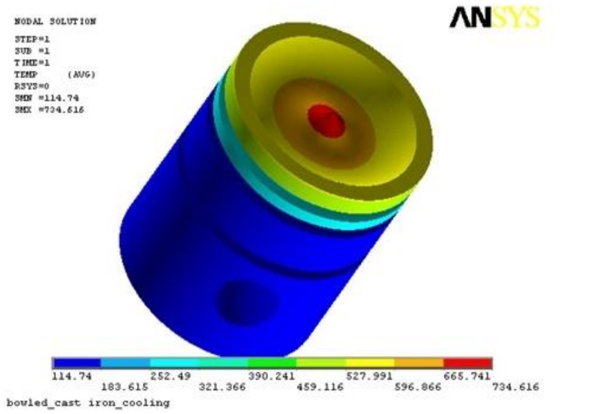

Figure 6.3.5 Temperature distributions of the piston made up of **cast iron** in bowled piston geometry

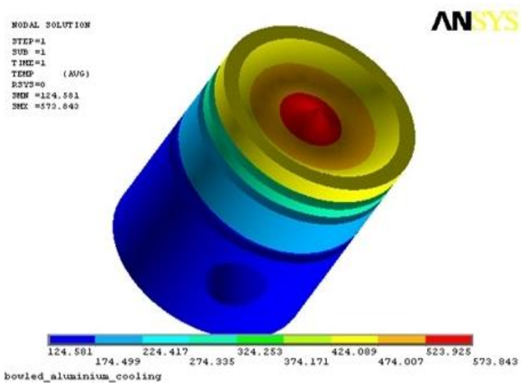

Figure 6.3.6 Temperature distributions of the piston made up of **aluminium** in bowled piston geometry

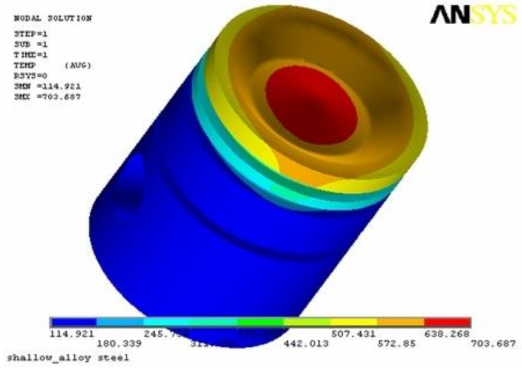

Figure 6.3.7 Temperature distributions of the piston made up of **alloy steel** in shallow piston geometry

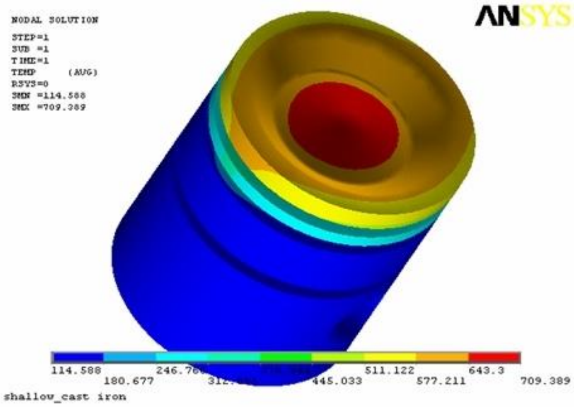

Figure 6.3.8 Temperature distributions of the piston made up of **cast iron** in shallow piston geometry

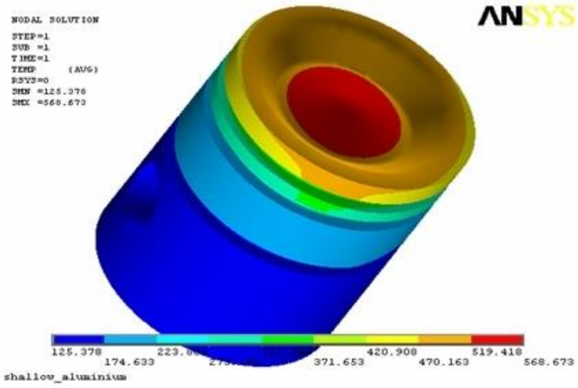

Figure 6.3.9 Temperature distributions of the piston made up of aluminium in shallow piston geometry

7.1 The **maximum temperature** reached in different piston geometry is summarized below

Table: 7.1. Maximum Temperature with cooling

Shape	Material	Thermal Conductivity (W/Mk)	Peak Temp (^{O}c)
Flat	Alloy Steel	52	707
Flat	Cast iron	46	718
Flat	Aluminium	220	518
Bowled	Alloy Steel	52	724
Bowled	Cast iron	46	734
Bowled	Aluminium	220	573
Shallow	Alloy Steel	52	703
Shallow	Cast iron	46	709
Shallow	Aluminium	220	568

8.1 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.Now that most of the regions in the piston are in controlled temperatures. Therefore it is necessary to have dedicated cooling mechanisms for piston without which material melting may not be a surprise. It is also interesting to note that more heat is always concentrated at the centre of the piston. This is so in all piston geometries. 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 8.1 Comparison of both (with and without) the thermal analysis

Shape of the piston crown	piston material	Thermal conductivity (k) in W/mK	Peak material temperature without cooling in °C	Peak material temperature with cooling in °C
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	1988	573
Shallow	Alloy steel	52	1363	703
Shallow	Cast iron	46	1991	709
Shallow	Aluminium	220	1584	568

As can be seen from the above plots, it is very clear that cooling mechanisms are essential for an engine. Most of the regions in the piston were brought to a controlled temperature when the cooling mechanisms were simulated. Aluminium piston runs very cooler than the alloy steel and cast iron made pistons. As it has been already mentioned, this simulation is basically peak moment simulation in which critical moments (at the point of combustion) were simulated. So very practically speaking, temperature in the engine will have to rise to these levels even with water and oil cooling [1, 7, 5, 16]. An engine running at very stable condition, the surface temperature of the piston is around 500-700 °C. This range is in fact varies during burning cycle. This range is maximum during the combustion moments.

9.1. Conclusion

Internal combustion engines have been one of the active areas of research for many academic researches since the inception. Almost all of the components in an internal combustion engine are subjected to heat and structural loads.

9.1.1 The current study emphasis on stress, strain, temperature, heat flux, thermal gradient, velocity and pressure distributions in the component materials.

9.1.2 The study was carried out using the Finite Element Methods Approach

9.1.3 The type of study is peak moment simulation which means that only the conditions prevailing at the point of combustion are simulated

9.1.4 Finite Element Analysis is a way to simulate loading conditions on a design and determine the design's response to those conditions.

9.1.5 Structural analysis is used to determine deformations, strains, stresses, and reaction forces.

9.1.6 Thermal analysis is used to determine the temperature distribution in an object. Other quantities of interest include amount of heat lost or gained, thermal gradients, and thermal flux.

9.1.7 CFD is used to determine the flow distributions and temperatures in a fluid

9.1.8 All the analyses were carried out for different boundary conditions, different geometries and different materials properties.

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