Analysis of Thermal Stresses Acting on Piston of C.I. Engine

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Abstract— generally the piston, made of Al Alloy, is a crucial part of internal combustion engines. When the combustion of fuel takes place in heavy diesel engine cylinder, high temperature and pressure develops. Because of high speed and at high loads, the piston is subjected to high thermal and structural stresses. If these stresses exceed the designed values, failure of piston may take place. The software "Pro-E Wildfire" is used to establish the three-dimensional geometry model of the diesel engine piston. Then, the model is imported into ANSYS to set up a finite element model. In this work thermal stresses on piston is calculated by finite element analysis software. From results, it reveals that thermal stresses are existed on the piston and total deformation with thermal load. The conclusion of this study is that, material type of high thermal conductivity is considered better than material type of low thermal conductivity, because the maximum temperature is found in Carbon- Steel piston than Aluminum -Alloy piston. This means that the Aluminum- Alloy is considered better than the Carbon-Steel. And also due to increase in thermal Conductivity, leads to reduction in temperature at piston crown surface and increase in temperature of piston skirt.

Key words: FEM, Thermal stress, IC-engine, Al alloy, Carbon steel

I. INTRODUCTION

A piston is a component of reciprocating IC engines. It is the moving component that is contained by cylinder and is made gas-tight by piston rings. In an engine, its purpose is transfer force from expanding gas in the cylinder to the crankshaft via a piston rod and/or connecting rod. As an important part in an engine, piston endures the cyclic gas pressure and the inertial forces at work, and this, such a piston side wears, and piston head/crown cracks and so on. The investigations indicate that the greatest stress appears on upper end of the piston and stress concentration is one of the main reasons for fatigue failure. On the other hand piston overheating-seizure can only occur when something burns or scrapes away the oil film that exists between the piston and cylinder wall.

Understanding this, it's not hard to see why oils with exceptionally high film strengths are very desirable. Good quality oils can provide a film that stands up to the most intense heat and the pressure loads of a modern high output engine. Thermal analysis is a branch of materials science where the properties of materials are studies as they change with temperature. FEM method are commonly used for thermal analysis. Due to the complicated working environment for the piston; on the other hand, the FEA for the piston became more difficult, on the other hand, through there have many methods which are put forward to apply optimal design, the optimal parameters is not easy to determine. In this study, the piston is used in low idle and rated speed diesel engine. In order to enhance the engine dynamic and economic, it is necessary for the piston to implement optimization.

The mathematical model optimization is established firstly, and the FEA is carried out by using the ANSYS software. Based on the analysis of optimal result, the stress concentration on the upper end of the piston has become evaluate, which provides a better reference for the piston.

II. FINITE ELEMENT MODEL

Establish reasonable and accurate finite element model is the most important part of the piston finite element analysis, thus carrying out analysis by marking element grids to obtain the accurate results finally. According to the structural symmetry of the piston, in order to be convenient for calculation and decrease workload, cut the established piston model to maintain 1/4 and then import the model to the finite element software for the finite element analysis to the piston according to the fine interface between the modeling software and the finite element analysis software. During the importing process, some details have been omitted, such as the chamfer and the snap ring of the piston pin etc. The geometrical model for the piston is as shown in Figure 1. Physical Properties of the Material is as shown in table1. During the mesh generation for the piston model, based on experiences and with several trials, the eight-node hexahedron cell SOLID70 is selected in this paper.

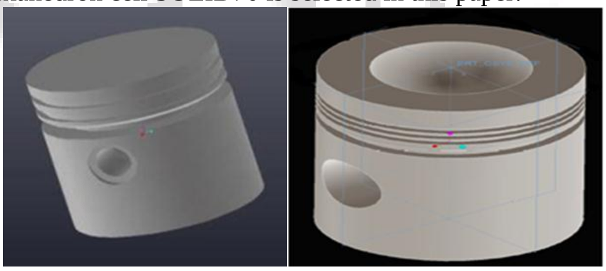

Fig. 1: Geometric model for the Flat and Bowl surface piston

The physical properties of the material are given below-

The following are the mechanical properties of aluminium alloy and carbon steel that have been taken from the review paper [1].

Properties	**Unit**	**Aluminum Alloy**	**Carbon Steel**
Poisson's ratio	-	0.33	0.28
Modulus of elasticity	GPa	73	210
Shear Modulus of elasticity	GPa	28	80
Coefficient of thermal expansion	$10^{-6}/^{o}C$	23	14
Density	KN/m^3	28	77
Thermal conductivity	W/m.K	177	50.36

Table 1: Physical properties of the materials

III. THEORETICAL ANALYSIS

The function of the piston is to absorb the energy released after the Air/Fuel mixture is ignited by the high temperature .The piston then accelerates producing useful mechanical energy. To accomplish this, the piston must be sealed so that it can compress the mixture of air and fuel and does not allow gases out of the combustion chamber. This can be accomplished by the piston rings which also help to prevent oil from entering the combustion chamber from underneath the piston. Another function of the rings is to keep the piston from contacting the cylinder wall. Less contact area between the cylinder and piston reduces friction, thereby increasing efficiency [1]. In the previous works a paper analyzed thermally pistons made from cast iron and aluminum alloy. Their results are indicated that the thermal flux is very high in the center of piston crown and it is low at the piston skirt. The temperature of the cast iron piston is higher than the temperatures of aluminum alloy piston by a value about to 40-80 ^{o}C [2].

Also by carrying out an analysis and experiments on the piston , and depending on the principle of cooling piston with oil in order to permit the piston to carry more thermal loads without having more damages with increasing the engine speed rate . And there are two types of pistons according to the cooling case , the first type is the piston with the cooling gallery in which the cooling oil is passed , and the second type is the solid piston where the cooling is limited to the under crown surface only .It has been developed a program for analysis diesel engine piston.

This program depends on the Finite Elements method in the procedure of analysis. Using this Program, a diesel engine piston with coolinggalleryandaone-quarter3-dimension piston model was designed, it was noted that the highest thermal deformations occurs at the piston crown region.

IV. CALCULATION OF HEAT TRANSFER COEFFICIENTS

The piston receives the heat from the hot gases formed by burning mixture of a particular air-fuel ratio, due to which boundary conditions around the piston body are different from region to region. In this work calculation of the thermal analysis depends on the theories of the convection heat transfer analysis that could be applied to piston.

A. Heat Transfer Co-Efficient between Hot Gases and Piston Crown Surface:

The mathematical description of the forced fluid flow on a cylinder surface is so complicated. Where as in theparts of an internal combustion engine especially the piston, the effect of the hot gases on it is very complicated, andin order to calculate the heat transfer coefficient at the piston crown surface, the heat transfer is described as aforced-convection heat transfer inside a cylinder. The heat transfer from the combustion gases is assumed to be Similar to the turbulent heat transfer of gases in a cylinder as follows:[1]

$$Nu = C\,Re^{m}\,Pr^{n} \text{----- (1)}$$

Where: m = exponent is typically assumed to be 0.8 for fully developed turbulent flow.
n = 0.3 or 0.4 for the cooling or heating respectively.
C = Constant is to be found from the experimental studies.

Benson mentioned that Gunter F Hohenberg presented a developed relationship for the equation-(1) by using the cylinder volume as a function of the piston diameter.

$$h = 226.6\,P^{0.8}T^{-0.4}(V_p + 1.4)^{0.8} \text{--------- (2)}$$

Therefore equation (2) will be the basic equation for a heat transfer coefficient calculation at piston crown surface.[1]

B. Heat Transfer Coefficient at Piston under Crown Surface:

The piston under crown surface is considered a very complex geometry shape due to the existence of the ribs and the piston pin bosses, where heat transfer calculations will not be easy to evaluate the heat transfer coefficient in each area at this region. Therefore according to these reasons, the assumption which is made here shows that the under crown surface is assumed to be a cylinder and the lubricant oil moving along the surface of cylinder at a particular velocity which is equivalent to the mean piston velocity at a particular temperature. According to this assumption the satisfactory correlation for this case is the Ditus-Poelter correlation which satisfied turbulent forced convection heat transfer on the cylinder surface; this correlation gives the Nusselt number, hence the heat transfer coefficient can be obtained as shown below [2]

$$h_{oil} = 0.023\,D_h^{-0.2} k_{oil}\,[\,\rho_{oil} x\,U_{oil} / \mu_{oil}\,]\,Pr^{0.3} \text{-------(3)}$$

So equation (3) is the equation for calculating the heat transfer coefficient at the piston under crown surface.

V. THERMAL BOUNDARY CONDITIONS

The thermal boundary conditions consists of applying a convection heat transfer coefficient and bulk temperature to the piston crown and the piston under crown surfaces with a constant temperature of about 373K.[1].

A. Boundary Conditions on Piston Crown Surface:

From equation (2) at mean gas pressure of 7.16bar, bulk temperature of 925K, and piston velocity of 5.5m/sec, so the heat transfer is equal to-[1]
hg = 334 W / m ^{2}

B. Boundary Conditions on Piston under Crown and Inner Walls of the Piston Skirt:

The heat transfer coefficient applied to the piston under crown surfaces and on the inner walls of the piston is computed from equation (3) according to the oil flow speed, the coefficients for each speed are shown in the following table.

Distribution of Heat Transfer Coefficient for Oil with Oil Flow Speed.

U_{oil} , m/sec	h_{oil} , W/m^2
30	584

VI. FINITE ELEMENT ANALYSIS

ANSYS is the usually preferred analysis software package because of its functionality. In this interface, you can apply forces, pressures, torques, temperature etc on the models and see how the stresses develop. If you are good at FEM, you can implement your own mesh generation techniques (otherwise, ansys will generate the mesh for you; all u have to do is to apply to conditions over the geometrical model--> heat sources, forces, etc...).

A. For Flat Surface Piston: Aluminum Alloy Vs Carbon Steel:

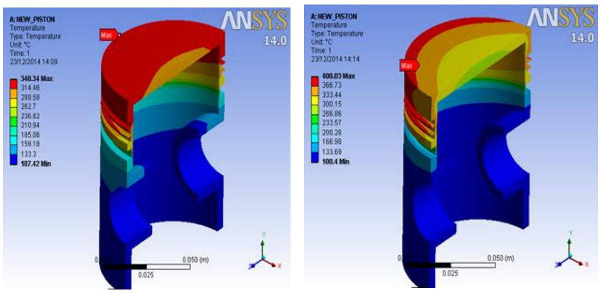

Fig. 2: Comparison between Temperature Distribution for aluminium alloy and carbon steel

On the basis of above figure we can conclude that the temperature of aluminum alloy (340.34 ºC) is less than the temperature of Carbon steel (400.03 ºC) due to higher thermal conductivity. The temperatures are high at the top and become low at bottom due to thermal conductivity of the material. Aluminum alloy having higher thermal conductivity than carbon steel.

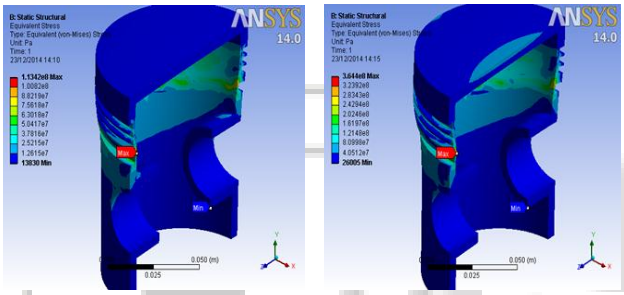

Fig. 3: Comparison between Thermal Stress for aluminum alloy and carbon steel

Finally, the thermal stress acting on Aluminum Alloy is less as a value of 1.134 × 10^8 Pa than the thermal stress acting on Carbon steel as a value of 3.64 × 10^8 Pa. Hence, the thermal stresses on aluminum alloy are less than Carbon Steel because of low temperature region and high thermal conductivity.

From the above figures, we calculated the temperature distribution and thermal stresses for flat surface aluminum alloy and carbon Steel piston. So we can observe that the temperature is maximum in carbon steel piston as 400.03ºC than aluminum alloy as 340.34 ºC due to low thermal conductivity of carbon steel.

Again, we optimize the piston for calculating the operating results with bowl surface piston for the same material.

B. For Bowl Surface Piston: Aluminum Alloy Vs Carbon Steel:

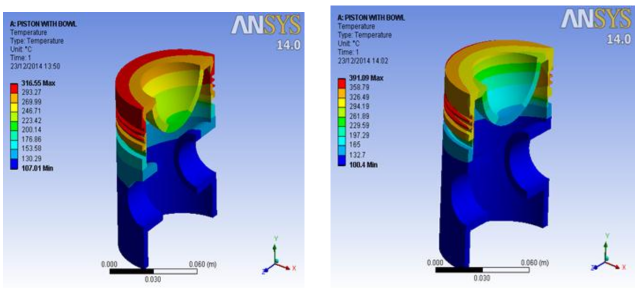

Fig. 4: Comparison between Temperature Distribution for aluminum alloy and carbon steel

On the basis of above figure we can conclude that the temperature of aluminum alloy (316.55ºC) is less than the temperature of Carbon steel (391.09 ºC) due to higher thermal conductivity. The temperatures are high at the top and become low at bottom due to thermal conductivity of the material. Aluminum alloy having higher thermal conductivity than Carbon Steel.

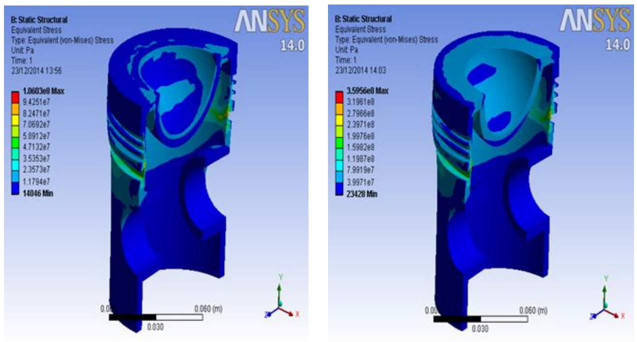

Fig. 5: Comparison between Thermal Stress for aluminum alloy and carbon steel

Finally, the thermal stress acting on Aluminum Alloy is less as a value of 1.06 × 108Pa than the thermal stress acting on Carbon steel as a value of 3.50 × 108 Pa. Hence, the thermal stresses on aluminum alloy are less than Carbon Steel because of low temperature region and high thermal conductivity.

Graphical Representation of comparison between maximum and minimum temperature of Carbon Steel and Aluminum alloy bowl piston are as follows-

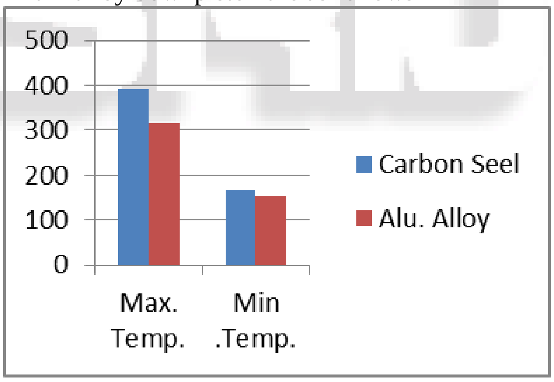

Fig. 6: Max. temp. and Min. temp. for Carbon Steel and Aluminum Alloy

Hence, from the above graph we can see that the temperature are higher at the top surface in Carbon Steel than the aluminum alloy due to higher thermal conductivity and also the lower temperature region are in the bottom surface in the aluminum alloy because of good thermal as well as mechanical property.

VII. EFFECT OF TEMPERATURE ON DEFORMATION

It is found that the piston crown surface will have maximum deformation due to high temperature region. Hence, Carbon Steel piston will have more deformation when compared to Aluminum Alloy piston, because piston crown surface temperature of Carbon Steel piston is higher than the piston crown surface temperature of Aluminum Alloy piston.

VIII. RESULTS AND DISCUSSION

Properties	Carbon Steel Flat Piston	Aluminum Alloy Flat Piston	Carbon Steel Bowl Piston	Aluminum Alloy Bowl Piston
Temperature (°C)	400.03	340.34	391.09	316.55
Deformation (m)	0.00035	0.00021	0.00029	0.00022
Heat Flux (W/m^2)	1.46 × 10^6	3.30 × 10^6	1.43 × 10^6	3.16 × 10^6
Shear Stress (Pa)	1.88 × 10^8	3.30 × 10^7	1.87 × 10^8	5.53 × 10^7
Thermal Stress (Pa)	3.64 × 10^8	1.13 × 10^8	3.59 × 10^8	1.06 × 10^8

Table 2: Results for Piston with Optimization

From the given work the results are-

(1) The maximum temperature in the carbon steel flat piston is 400.03°C which is higher than aluminum alloy flat piston is 340.34 °C. also, the maximum temperature in the carbon steel bowl piston is 391.09°Cwhich is higher than aluminum alloy bowl piston is 316.55 °C . So, by comparing all the results aluminum alloy with bowl piston having least temperature than the other pistons.

(2) Due to the maximum temperature the deformation is more in carbon steel flat piston is 0.0003 m and the minimum deformation is in the aluminum alloy bowl piston because of least temperature is 0.0002 m.

(3) Finally, the thermal stresses acting on aluminum alloy bowl piston is minimum as 1.06 × 10^{8}Pa and maximum in 3.64 × 10^{8}Pa.

IX. CONCLUSION

The temperature is defined as the measure of the molecular activity of a substance where higher the temperature greater the movement of molecules. Since piston is subjected to non- constant thermal loads from region to region, the temperatures of the piston is constant but will be distributed along piston body from maximum temperature to minimum temperature.From the given table, we can see that the Flat Carbon steel piston is having highest temperature than aluminum alloy bowl piston. And also the thermal stresses are higher in Carbon Steel Flat piston than aluminum alloy bowl piston. This is due to the thermal conductivity is increased, the amount of heat flow will be high and this causes a temperature drop between the warm and cold walls while when thermal conductivity value is decreased the temperature drop is increased by a particular value. From this comparison it is noted that the first compression ring in a Carbon Steel piston receives a high quantity of heat than the aluminum alloy piston.

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