Thermal Stress Analysis of Diesel Engine Piston

B.R. Ramesh and Kishan Naik

Abstract--- *Internal combustion engine consists of many parts. Piston is heart of IC engine, which works on high temperature. Beside this, it works under periodic heat load. The thermal-stress analyses are investigated on a diesel engine piston made of Aluminium-Alloy and Carbon-Steel.*

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 Aluminium-Alloy piston. This means that the Aluminium-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.

Keywords--- *Finite Element Method, Thermal stress, IC-engine, Aluminium-Alloy, Carbon-Steel*

I. INTRODUCTION

PISTON is considered to be one of the most important parts in a reciprocating engine in which it helps to convert chemical energy obtained by the combustion of fuel into useful mechanical power.

The purpose of the piston is to provide a means of conveying the expansion of the gases to the crankshaft through the connecting rod. Piston is essentially a cylindrical plug that moves to and fro in the cylinder. It is equipped with piston rings to provide a good seal between the cylinder wall and piston.

The efficiency and economy of the engine primarily depends on the working of piston. It must operate in the cylinder with minimum friction and should be able to with stand high explosive force developed in the cylinder and also the very high temperature ranging from 750K to 3100K(500ºC to 2,800ºC) during operation. The piston should be as strong as possible. However its weight should be minimized as far as possible in order to reduce the inertia due to its reciprocating mass.

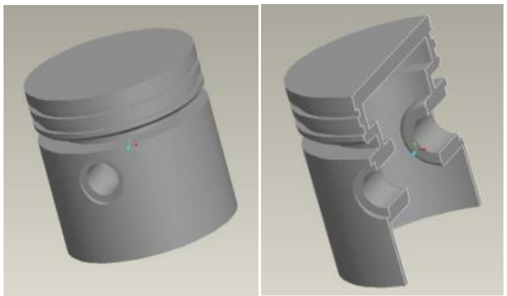

Figure (1): 3-Dimensional View of Piston

Among engine components exposed to thermal effects, the piston is considered to be one of the most severely stressed, where a high amount of the heat transferred to a coolant fluid goes through it, this amount depends on the thermal conductivity of the materials employed, average speed and geometry of the piston. [1]

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In this work, temperature distribution analysis is carried out for a one half of Kirloskar-TV1 4-Stroke, Vertical Diesel engine piston as shown in Figure (1). In order to carry out the analysis, a finite element code ANSYS is used. The simulation performed in this work is steady-state three-dimensional.

II. 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-fuel and does not allow gases out of the combustion chamber. [1][2]

In the previous works a paper analyzed thermally pistons made from Cast-Iron and Aluminium-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 40-80 ºC. [1] [3]

III. CALCULATION OF HEAT TRANSFER COEFFICIENT

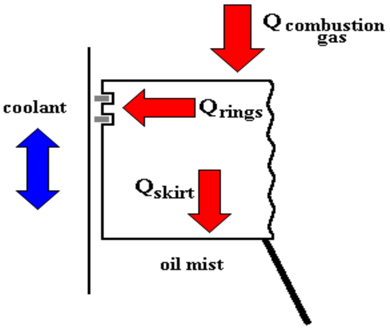

Figure (2): Heat Transfer in Piston

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.

3.1 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 the parts of an internal combustion engine especially the piston, the effect of the hot gases on it is very complicated, and in order to calculate the heat transfer coefficient at the piston crown surface, the heat transfer is described as a forced-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. [5]

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. [6]

$$h_g = 226.6\ P^{0.8}\ T^{-0.4}\ (V_P+1.4)^{0.8} \text{ ---- (2)}$$

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

3.2 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- [7]

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

So equation (3) is the equation for calculating the heat transfer coefficient at the piston under crown surface. [1] [8]

IV. DEVELOPMENT OF THE PISTON MODELS

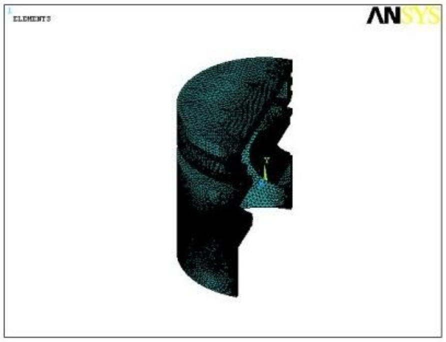

Figure (3): Meshed One-Half of Piston

This section consumed very much time and effort in building three-dimensional geometry model of the diesel engine piston using modeling tool.

The final step in the building process is dividing three-dimensional geometry model of the diesel engine piston into finite elements using meshing process tool after choosing an element type in order to justify the thermal analyses in 3-dimensions which is Tetra element, the meshed volumes are shown in Figure (3).

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]

5.1 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]

$$h_g = 334 \text{ W / m}^2$$

5.2 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 (4). [1]

Table (1): Distribution of Heat Transfer Coefficient For Oil With Oil Flow Speed [1]

U_{oil}, m/sec	h_{oil}, W/m² K
30	584

VI. RESULTS AND DISCUSSION

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. The maximum values of the temperatures are studied according to the thermal effects on the temperature distribution. [1]

In this work, two material alloys are used in the thermal analysis of the piston. Piston materials are of Aluminum-Alloy having a thermal conductivity of 177 W/m-K, and Carbon-Steel material having a thermal conductivity of 50.36W/m-K. [9]

6.1 Temperature Distribution in Aluminium-Alloy Piston

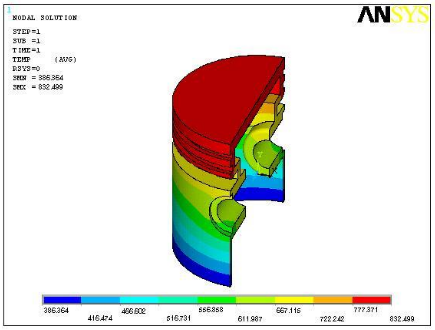

Figure (4): Temperature Distribution in Aluminium-Alloy Piston

The temperature distributions in the piston for Aluminum-Alloy are shown in Figure (4). The maximum temperature in the piston is equal to 832.499K in the region of piston crown and the minimum temperature is equal to 386.364K in the region of piston skirt.

Shown in Figure (5), where the maximum temperature of 924.999K is found in the region of piston crown and the minimum temperature of 373.718K in the region of piston skirt

6.2 Temperature Distribution in Carbon-Steel Piston

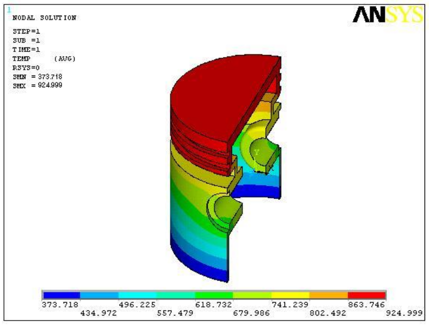

Figure (5): Temperature Distribution in Carbon-Steel Piston

In a piston made of Carbon-Steel material the temperature distributions in the piston are shown in Figure (5), where the maximum temperature of 924.999K is found in the region of piston crown and the minimum temperature of 373.718K in the region of piston skirt

6.3 Effect of Thermal Conductivity on Temperature Distribution

A comparison between pistons made of Aluminum-Alloy and Carbon-Steel, shows that the maximum value of a temperature in the piston of Carbon-Steel is higher than the maximum temperature in the piston of Aluminum-Alloy by 92.5K in the region of piston crown, whereas the minimum temperature in the Carbon-Steel piston is smaller than the minimum temperature in Aluminum-Alloy piston by 12.646K in the region of piston skirt. This is due to the lowering value of the thermal conductivity for the Carbon-Steel piston of that in the Aluminium-Alloy piston. If the thermal conductivity is increased, the amount of the 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.

6.4 Effect of Temperature on Deformation

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

VII. CONCLUSION

The maximum temperature is found in Carbon-Steel piston than the Aluminum-Alloy piston. Therefore first compression ring in a Carbon-Steel piston receives a high quantity of heat than the Aluminum-Alloy piston.

The difference between maximum temperature in the Carbon-Steel piston and Aluminium-Alloy piston is 92.5K in the region of piston crown and minimum temperature in the Carbon-Steel piston and Aluminum-Alloy piston is 12.646K in the region of piston skirt. This is due to increase in thermal conductivity.

If the thermal conductivity is increased, the amount of the heat flow will be high. Therefore the material type with high thermal conductivity is considered better than the material type of low thermal conductivity. This means that the Aluminum-Alloy is considered better than the Carbon-Steel.

Maximum deformation is found in the Carbon-Steel piston than the Aluminium-Alloy piston. And this can be considerably reduced by increasing the thickness of piston crown due to which quantity of heat absorbed will be increased by which the piston crown surface temperature can be reduced and also by increasing thermal conductivity of piston material.

NOMENCLATURE

A: Flow cross-section area (m^2)
C: Constant
D: Cylinder bore (m)
D_h: Hydraulic diameter (m)
h: Convection heat transfer coefficient (W/m^2K)
h_g: Heat transfer coefficient of gas ($W/m^2 K$)
h_{oil}: Heat transfer coefficient of oil ($W/m^2 K$)
k: Thermal conductivity (W/m K)
k_{oil}: Thermal conductivity of oil (W/m K)
m,n : Constants.
Nu : Nusselt number
P : Mean gas pressure (bar)
Pr : Prandtle number
Re : Reynolds number
T : Bulk temperature (K)
U_{oil} : Oil flow speed (m/sec)
V_p : Piston mean velocity (m/sec)
ρ_{oil}: Oil fluid density (kg/m^3)
μ_{oil} : The Dynamic viscosity of oil (kg/m sec

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