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Design and Thermal Analysis of Diesel Engine Piston

Chiranjivi Dahal[1], Shacheendra Kishor Labh[2], Dipendra Sah[3*]

[1,2,3] *Department of Mechanical and Automobile Engineering, IOE, Pashchimanchal Campus*

**Corresponding email: <pas075bme048@wrc.edu.np>*

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Abstract

The piston of an IC engine bears the number of forces before transferring the force to the crankshaft. The main objective of this study to find out the temperature distribution and deformation in diesel engine piston when it is acted upon by gas pressure and high temperature from burning gas. Aluminum alloy has been chosen for the analysis purpose. Suitable data has been assumed to design the geometry of piston. The analysis of the temperature and deformation due to temperature are performed on FEA based software. The boundary conditions include temperature from burning gases and pressure exerted by gas in piston. The results show the crown of piston has the maximum temperature with value of 196 °C and maximum deformation of 0.198 mm.

Keywords: *piston, temperature, stress, FEA*

1. Introduction

An internal combustion (IC) engine is a type of heat engine that uses the combustion of fuel to provide energy to move a vehicle or other machinery. The most common type of internal combustion engine is the petrol engine, which is used in cars and light-duty vehicles. Diesel engines, which use a different type of fuel, are also common in trucks and heavy equipment. The major components of IC engine include piston, connecting rod, crankshaft, inlet and exhaust valves, cam shaft, and valve drive mechanism.

A piston is a cylindrical component that is used to transfer mechanical force from expanding gas in an IC engine to the crankshaft. It is typically made of metal and sealed at one end by a piston ring, which prevents the fluid or gas from leaking out of the cylinder. The other end of the piston is connected to the connecting rod, which converts the reciprocating motion of the piston into rotary motion. In an engine, the combustion of fuel generates a high-pressure force that pushes the piston down the cylinder, creating mechanical energy that can be used to power a vehicle or other machinery. Other forces acting on the piston include the force exerted by the connecting rod on the piston, the friction between the piston and the cylinder, and the force exerted by the compression or expansion of gases in the cylinder. Additionally, the piston is also subjected to thermal expansion and contraction due to changes in temperature.

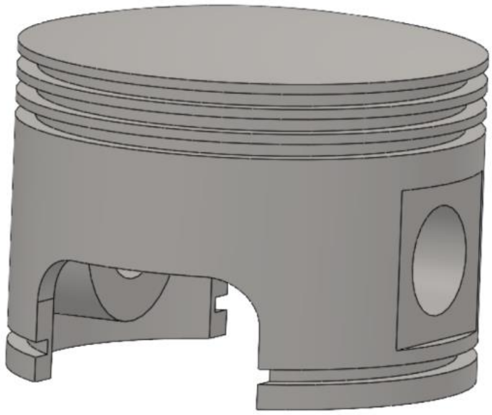

Figure 1: IC Engine Piston

1.1 Temperature and pressure distribution in piston

Temperature can have a significant effect on the performance and longevity of a piston in an internal combustion engine. High temperatures can cause the piston to expand and potentially seize in the cylinder, while low temperatures can cause the piston to contract and potentially cause gaps between the piston and cylinder walls. (P Gustof, 2019). It is important to have the engine running at the optimal temperature range, too high or too low temperature can cause damage to the engine components. Therefore, many modern engines use cooling and heating systems to regulate the temperature of the pistons and other engine components.

The temperature of a piston in an internal combustion engine can vary depending on a number of factors, including the efficiency of the engine, the load on the engine, and the ambient temperature. During normal operation, the temperature at the top of the piston, which is closest to the combustion chamber, can reach temperatures of 600-800 ° C, while the bottom of the piston, which is in contact with the cylinder wall, can reach temperatures of 150-300 °C. (Taylor, 1957), (Woschni, 1967), (Hohenberg, 1979), (Chang, 2004).

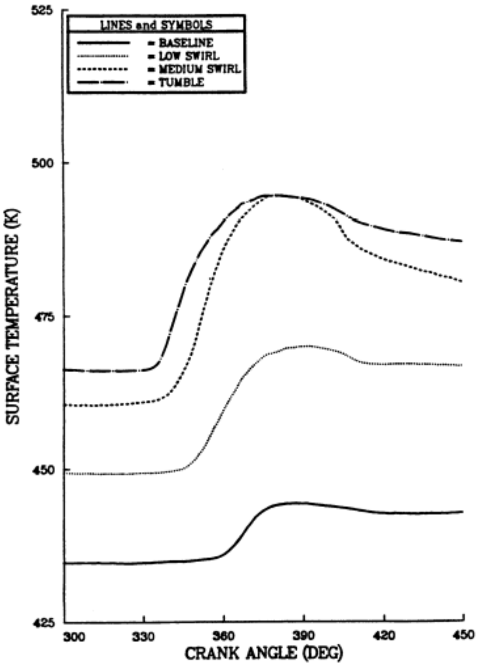

Figure 2 : Effects of flow configuration on surface temperature (Alkidas, 1990)

The high temperature of the piston can cause thermal expansion and contraction, which can lead to distortion and wear of an internal combustion engine can vary depending on the operating conditions of the engine, compression ratio, ignition timing and the type of fuel being used. In a petrol engine, the peak cylinder pressure can range from around 8 to 14 bar (120 to 200 psi) during the power stroke. In a diesel engine, due to its higher compression ratio, the maximum cylinder pressure can be as high as 25 to 30 bar (360 to 435 psi). (M. Akif Ceviz, 2011), (Randolph, 1990), (da Silva, 2019).

Researchers have done Finite Element Analysis for the temperature distribution in piston. (Ku, 2021), (P Gustof, 2019), (Qin Zhaoju, 2019), (M Frățița, 2019). For fully loaded piston maximum temperature obtained by simulation is 261.8 °C and minimum temperature is 121.25 °C from experiment (Subodh Kumar Sharma, 2015) .The experimental value for same condition is maximum 250 °C and minimum is 108 °C. (Subodh Kumar Sharma, 2015) . Heat supplied from the combustion gas by the author was 2023.9 Kw/hr. For the different heat flux of Q_1= 741 W, Q_2= 1397.27 W, Q_3= 1873.16 W, Q_4=2644 W, the researcher (Prasad, 1990) have obtained the maximum temperature of 145 °C, 200 °C,255 °C,290 °C respectively. The author (Yang Liu, 2022) have error margin of 5% in simulation with comparison with experiment.

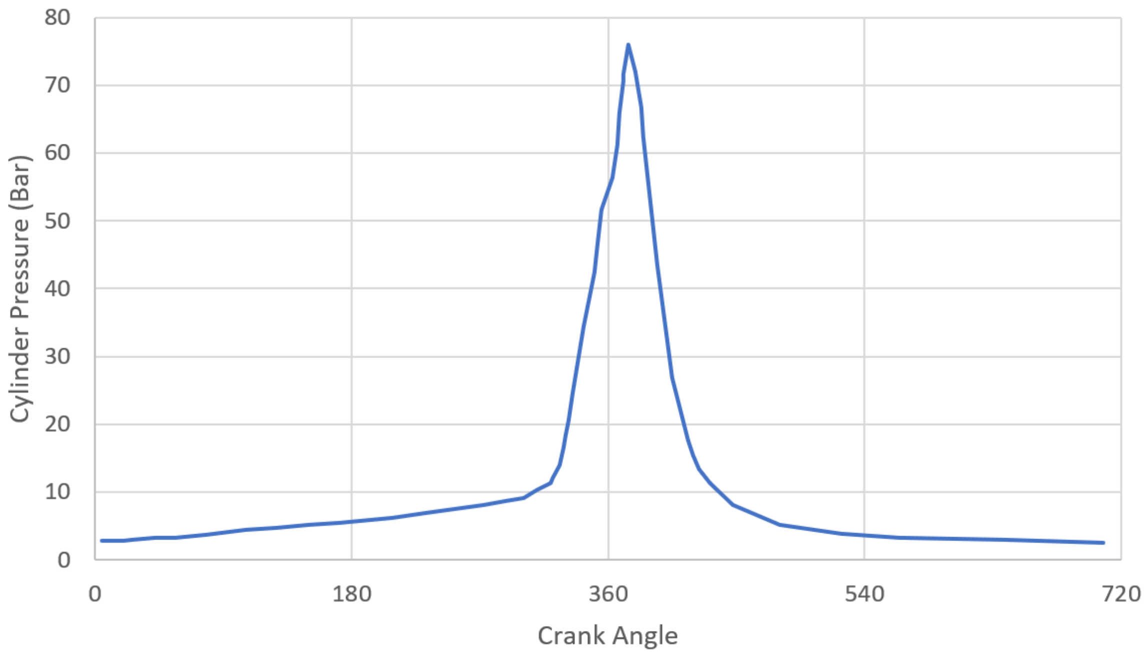

Figure 3: Variations of in-cylinder pressure in diesel engine with crank angle (Muhammad Usman Kaisan, 2021), (Torregrosa, 2007)

Researcher developed a semi adiabatic diesel engine by maintaining a thin layer of air gap on the inner surface of the sleeve and reported a 9% reduction in heat losses and a 3.5 % increase in thermal efficiency. (O. Pradeep Ram, 1983). To estimate the accurate heat flow rates, temperature distribution in piston is challenge for researchers. Thus, main purpose of this paper is to predict the temperature distribution in the IC engine piston and stress produced due to high temperature inside the cylinder.

2. Materials and Methods

2.1. Material for piston

Table 1: Aluminum Alloy Properties (John Gilbert Kaufman, 2004)

Description	Property
Tensile Strength (MPa)	70-505
Yield strength (MPa)	20-455
Elongation, %	<1-30
Hardness , HB	30-150
Thermal Conductivity (W/m . K at 25 C)	85-175
Fatigue limit (Mpa)	55-145

Coefficient of linear expansion at 20-100 C	17.6-24.7 x10^6 /C
Shear strength (MPa)	42-325
Modulus of elasticity, (Gpa)	65-80
Specific gravity	2.57- 2.95

2.2. Mathematical model

The temperature distribution in piston follows a definite pattern. The heat transfer methods are conduction, convection, radiation and heat generation trough friction between piston and cylinder wall. Heat transfer from radiation has not been included here as convection from the combustion is the most important heat generation source in an IC engine. (Martin Gonera, 2015) . Heat generation from friction is negligible compared to the combustion process (Gmbh, 2013). Heat transfer within the engine piston follows the Fourier's law.

$$q = -k.\frac{dt}{dx} \qquad \text{Equation 1}$$

Where,

-q is the heat flux,

-k is the heat conduction coefficient of the material

-dt is the temperature gradient

-dx is the thickness of the top land of the piston

Heat transfer due to convection is given by

$$Q = h\ A\ \Delta\mathrm{T} \qquad \text{Equation 2}$$

Where ,

-Q is the heat flux

-h is the convective heat transfer coefficient

-A is the area

- ΔT is the temperature gradient

The temperature of top surface of piston which comes in contact with hot gases is T_{gr} and has the mean heat transfer coefficient h_{gm}. The temperature of hot gases is $T_{gr}(\phi)$ and the heat transfer coefficient between the piston top surface and hot gases is $h_g(\phi)$. The value of $T_g(\phi)$

and $h_g(\phi)$ varies with crank angle ϕ. For a complete cycle the resulting temperature T_{gr} is given by Sitkei (Sitkei, 1974) in terms of following equation:

$$T_{gr} = \frac{(h_g T_g)m}{h_{gm}} \quad \text{Equation 3}$$

For the calculation purpose the value of T_{gr} and h_{gm} is taken as 400 C and 160 kcal/m2 hr C. (N. K. Dyachenko A. K., 1974), (N. K. Dyachenko S. N., 1969)

The value of the heat transfer coefficient $h_g(\emptyset)$ between piston top surface and hot gases, at any crank angle $(\emptyset)$ can be obtained by using indicator diagram by the formula given by Eichelberg (Eichelberg, 1939):

$$h_g(\emptyset) = 2.1\left(P_g(\phi)T_g(\phi)\right)^{0.5}(s)^{1.5}\ \text{kcal/m}^2\ \text{hr. °C} \quad \text{Equation 4}$$

Where $P_g(\phi)$ is the pressure (kgf/cm2), $T_g(\phi)$ is temperature (C) and s is the mean piston speed (m/s). The heat transfer coefficient between the bottom surface of the piston and the crank case (h_a), depends upon the type of cooling used, for ordinary conditions of operation of the engine, h_a varies from 50 to 150 kcal/m^2 hr. °C (V. P. Singh, 1986)

2.3. Geometrical and FE model of piston

The pistons used for analysis purpose has been designed based on guidelines provided by researchers. (Ku, 2021) The specification of engine is given be table below: The material used is aluminum alloy whose property is given by table 1. Aluminum alloy is suitable for speed higher than 6 m/s. (Bhandari, 2010). The equations used to calculate the dimensions of piston has been taken from Design of machine elements . (Bhandari, 2010) The calculated dimension is shown in Table 2.

Table 2: Piston Dimensions

Description	Property (mm)
Thickness of piston, t_H	10.28
Radial thickness of ring, t_1	3.44
Minimum axial thickness of ring, t_2	3.44
Top land thickness, b_1	12.34
Thickness of other land, b_2	3.44
Maximum thickness of barrel, t_3	11.10
Thickness of piston barrel at lower end, t_4	3.88
Outer diameter of piston pin, d_0	38.54

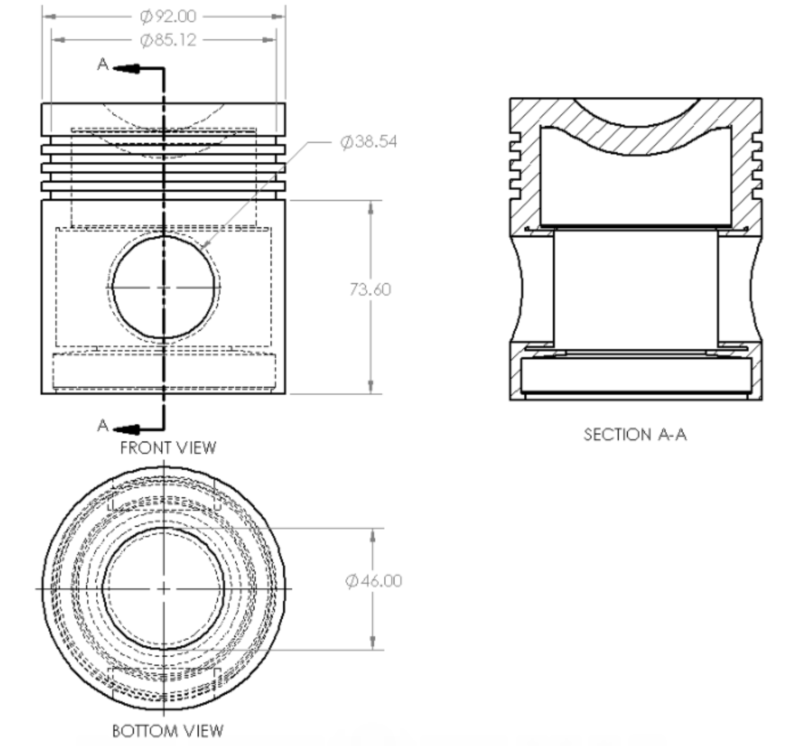

Figure 4: Geometrical model with dimensions

The 2D drawing of geometry can be seen in figure 4. The diesel engine piston with 4 compression rings were chosen for design. (R S khurmi, 2007). All the equations and assumptions were taken from Machine design text book. (R S khurmi, 2007). The diameter of piston is 92 mm and piston pin diameter is 38 mm. Other dimensions can be seen in figure 4.

2.4. Meshing

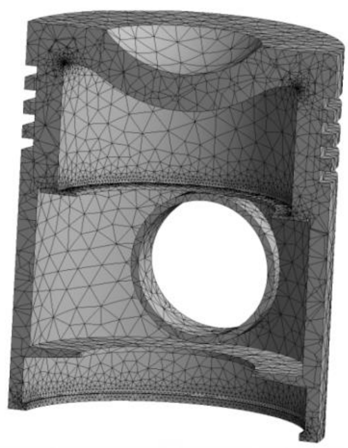

Figure 5: Mesh used in the simulation

Mesh consists of 165790 number of elements and 263164 number of nodes. Non linear mechanical mesh has been chosen for analysis of thermal stress. Cross section of mesh geometry can be seen in figure 5.

2.5. Boundary Condition

The boundary conditions for heat flux is Q_1 =638.89 W and Q_2 = 1397.27 W, where Q_1 and Q_2 are the heat flux generated by the burning gas. (Prasad, 1990) Two different values have been chosen for the input in simulation. The heat flux acts only on crown of the piston. The value of heat flux is dependent upon the gas temperature. The burning gas exchanges the temperature with the crown of the piston. Similarly, heat convection for various surfaces of piston has been

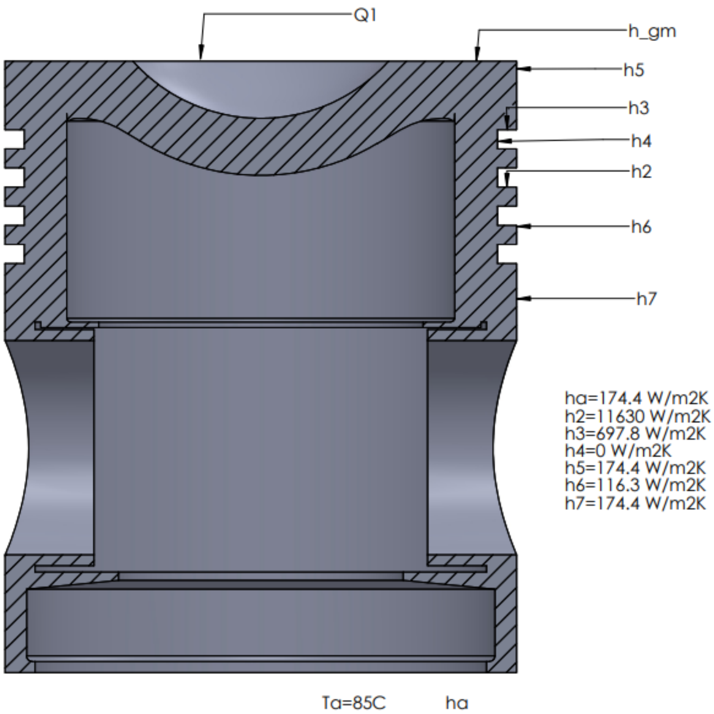

Figure 6: Boundary condition of an aluminum alloy internal combustion engine piston

shown in Figure 6. The Eichelberg equation (Eichelberg, 1939) has been used to determine the value of these heat convection. This value depends upon the piston material. The pressure of 6 MPa has been used as the force exerted by hot gases on surface of piston. Figure 3 shows the value of pressure range that can be used for diesel engine piston. For the static analysis piston pin location has been chosen as fixed support. The combine static and thermal analysis gives the thermal stress.

2.6. Methodology

The methodology consists of choosing the suitable material for piston which is Aluminum. The machine design hand data book was used to design the geometry of piston. 2D and 3D design of piston was done. The design geometry can be seen in figure 4. The designed geometry was imported in FEA based software and mesh was created. The mesh consisted of 165790 number of elements. The geometry was than analyzed by applying the boundary conditions shown in table 3 and figure 6. All the calculations were performed using Finite Element Analysis. After the iteration was completed, the results have been analyzed by comparing it with the previous literature. The geometry and mesh were modified to keep the error margin to less than 5%.

3. Results and Discussion

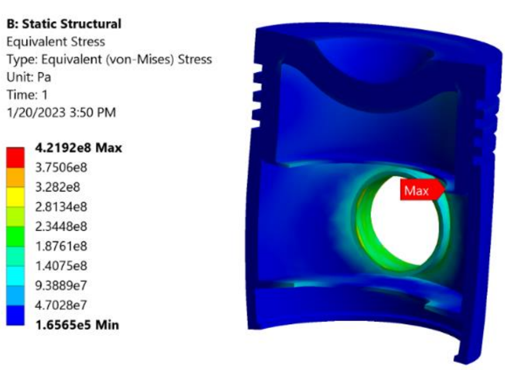

Figure 7: Stress due to Q_1

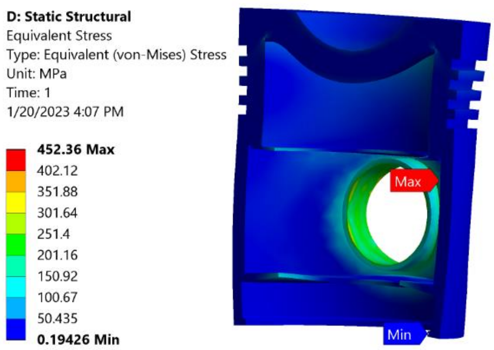

Figure 8: Stress due to Q_2

Figure 7 and 8 shows the thermal stress distribution in the piston when acted upon by the heat flux as shown in table 3. The result shows that the maximum pressure is acted on the piston pin. With maximum heat flux of 1397 W on the crown of piston, maximum pressure generated is 452 MPa and with minimum heat flux of 639 W, the pressure acted on piston pin is 421 MPa.

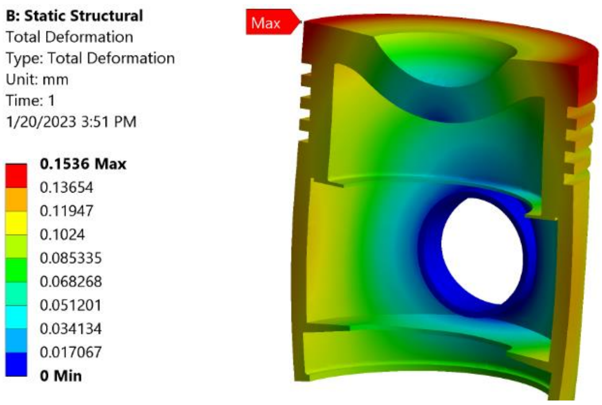

Figure 9: Deformation due to Q_1

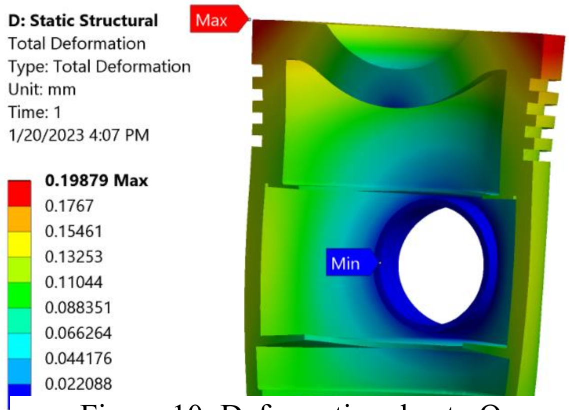

Figure 10: Deformation due to Q_2

Figure 9 and 10 shows the deformation due to thermal stress in the piston. It can be seen that location for maximum deformation is in crown of piston. This deformation is due to high pressure produced by gas and high temperature produced by same gas on surface of piston. With maximum heat flux of 1397 W, the maximum deformation is 0.198 mm and with minimum heat flux of 639 W maximum deformation is 0.153 mm. Piston clearance in the cylinder is 0.2% of cylinder bore. (Ifunanya Stella Ezeoye, 2019). Thus, deformation of piston is with in range of maximum limit of Aluminum alloy piston.

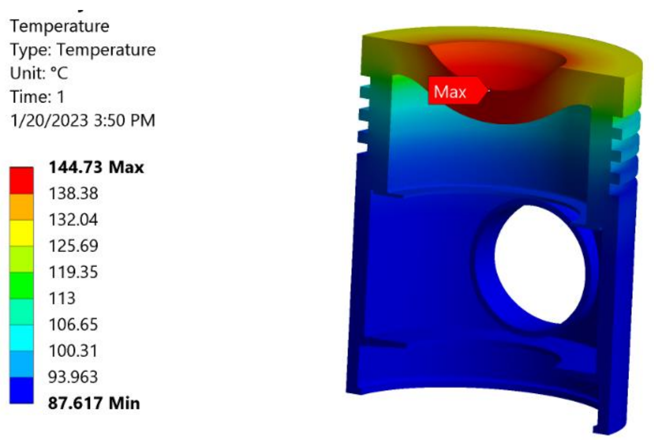

Figure 11: Temperature distribution due to Q_1

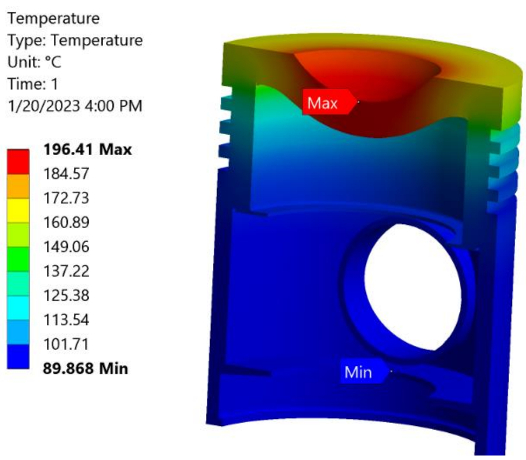

Figure 9: Temperature distribution due to Q_2

Figure 11 and 12 shows the temperature distribution due to heat flux Q_1 (639 W) and heat flux due to Q_2 (1397 W). The maximum temperature of 144.73 C was obtained when 639 W heat flux was applied. When 1397 W heat flux was applied, the maximum temperature was 196.41 C. Both of this maximum temperature was seen on crown of piston. For the same heat flux of Q_1= 639 W, Q_2= 1397 W the researcher (Prasad, 1990) have obtained the maximum temperature of 145 °C, 200 °C respectively. Thus, our results are within the acceptable range.

4. Conclusions

The temperature analysis of IC engine piston was carried out. The value for all the heat flux is within the range of 2% error. The thermal stress distribution due to pressure force was carried out.

- The maximum temperature in piston was found to be in crown of piston with value of 196 °C and the maximum deformation caused by this temperature was on crown of piston with the magnitude of 0.153 mm.

- These results have been verified with past work of author and the error margin is within 2% range.

The researchers have not considered the heat transfer due to lubricating oil, heat loss in coolant and heat transferred through piston fins. Further research work could be carried out by verifying the results with the experiments or using different numerical method for temperature estimation.

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