International Journal of Research in Engineering and Innovation (IJREI)
journal home page: http://www.ijrei.com
ISSN (Online): 2456-6934

Finite element heat transfer analysis of the cylinder head of a SI engine

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Abstract

Heat transfer is a crucial phenomenon in the internal combustion engine. For efficient working of the engine, heat transfer should be optimized such that there are no high temperature developed in the engine and also pressure inside the cylinder shouldn't fall below a certain critical value which may result in the loss of work.
A Finite Element model of cylinder head was analyzed for temperature and stresses by subjecting it to running engine conditions. The thermal analysis was performed by applying a constant thermal load for 60 sec. The thermal analysis was followed by structural analysis which is performed using the results of thermal analysis as load. The model was then tested for the different fin thickness. The temperature variation was observed for 2mm, 2.5mm, 3mm and 3.5mm thickness for all the three materials. It was observed that for 3mm thickness highest heat transfer occurred and therefore low temperatures were obtained.
Key words: Internal combustion, structural analysis, finite element.

1. Introduction

Heat transfer is a very wide field used in analysis of internal combustion engines. Heat transfer affects the parameters such as performance, emissions and also efficiency. It is said that for a given mass of fuel the higher the heat transfer to the combustion wall will reduce the average combustion pressure and temperature. This indirectly reduces the work done by the piston per cycle and these effects the specific power. Heat transfer in spark ignition engines is needed to determine thermal stress on material components. This will provide confidence to proceed the project and make sure that the design will not fail due to thermal stresses. Mainly the engine is not fully developed and not tested for any data. So the values of the parameters that are taken for the thermal modeling are based on theoretical values. This will be validated using experiments once the full engine is completed and further help to modify the engine in future works. The shape of isothermal lines and high temperature regions becomes more important in these studies. The experimental way will find these regions but are costly and time consuming. Analytical methods are almost equally good for fast conformation of these regions by using finite elements. With the information the amount of experiments can be reduced to save cost on a project. To represent the problem of heat transfer the model of the engine was analyzed. The temperature at the beginning of induction is that of clearance gases. Temperature in the cylinder falls rapidly as the cool charge is inducted. The temperature then rises during compression and is increased to a maximum by combustion process. The expansion process later decreases the temperature and the exhaust process then rapidly drops the gases temperature.

1.1 Parameters affecting Engine Heat Transfer [16]

Engine heat transfer depends on various parameters. Unless the effect of these parameters is known, the design of a proper cooling system will be difficult. The effect of various parameters is briefly discussed.

1.1.1 Fuel-air ratio

A change in fuel ratio will change the temperatures of the cylinder gases and affect the flame speed. The maximum gas temperature will occur at an equivalence ratio of about 1.12 i.e, at a fuel air ratio 0.075. At this fuel-air ratio will be maximum. However from experimental observations the maximum heat rejection is found to occur for a mixture, slightly leaner than this value.

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1.1.2 Compression Ratio

An increase in compression ratio causes only a slight increase in gas temperature near the top dead center; but because of greater expansion of the gas temperature near the bottom dead center, where a large cylinder wall is exposed. The exhaust gas temperature will also be much lower because of greater expansion so that the heat rejected during blowdown will be less. In general, as compression ratio increases there tend to marginal reduction in heat rejection.

1.1.3 Spark Advance

A spark advance more than the optimum as well as less than the optimum will result in increased heat rejection to the cooling system. This is mainly due to the fact that the spark timing other than the MBT value (minimum spark advance for the best torque) will reduce the power output and thereby more heat is rejected.

1.1.4 Pre-ignition and Knocking

Effect of pre-ignition is the same as advancing the ignition timing. Large spark advance might lead to erratic running and knocking. Though knocking causes large changes in local heat transfer conditions, the overall effect on heat transfer due to knocking appears to be negligible. However no quantitative information is available regarding the effect of pre-ignition and knocking on engine heat transfer.

1.1.5 Engine Output

Engine which are designed for high mean effective pressures or high piston speeds, heat rejection will be less. Less heat will be lost for the same indicated power in large engines.

1.1.6 Cylinder Wall Temperature

The average cylinder gas temperature is much higher in comparison to the cylinder wall temperature. Hence any marginal change in cylinder gas temperature will have very little effect on the temperature difference and thus on heat rejection.

2. Finite Element Modeling

The heat transfer model was created based on a fabricated engine that is going to be used for research purpose. Boundary condition to the problem was modeled based on standard heat transfer that would occur normally in a two stroke engine at steady state. This model was done with temperature distribution (conduction) at the spark plug location and convection is applied over the fin surface.

2.1 Boundary Conditions and Thermal Loading

Since the cooling system of the engine uses air, convection boundary is defined on all the outer surfaces (at fins) of the engine assembly. The value is taken as 25 W/m^2K [9] from running engine calculation. The engine speed used is the maximum theoretical speed which is 6000 rpm and a transient analysis is done for 60 second [1] the time the engine is running. The thermal load applied to the engine head is about 1070W [11].

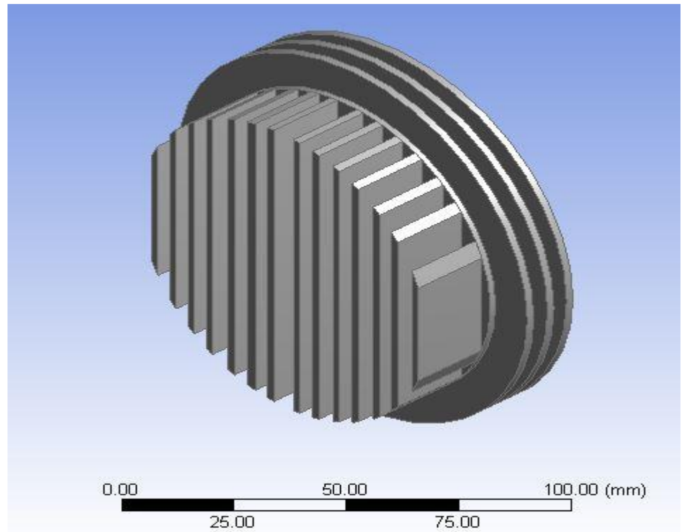

Figure1: 3-DCylinder head Model

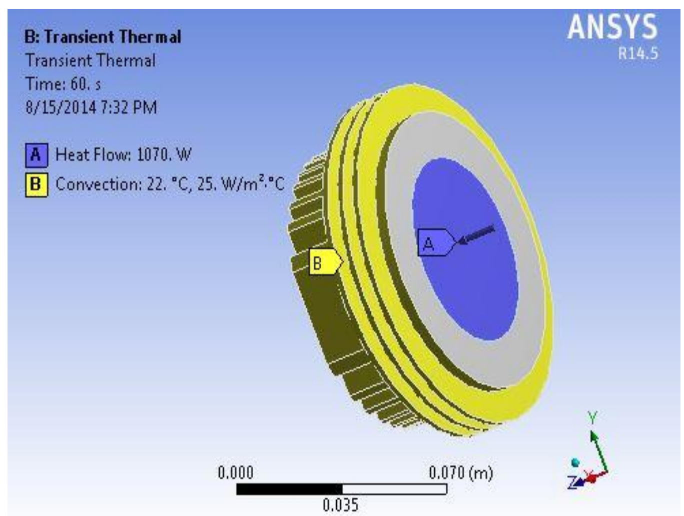

Figure 2: Thermal Loading of the cylinder head

2.2 Materials selection

Aluminum alloys A380, B390 and C443 were being chosen for their high thermal conductivity, specific heat, and high melting point. The heat transfer characteristics of the cylinder head will be analyzed for these three materials. Three different commercial alloys of aluminum were selected which are as follows.

Table 1: Material Selection

Material	Si	Fe	Cu	Mn	Ni	Zn	Sn	Al
A380	7.5-9.5	2	3-4	0.5	0.5	3	0.35	Rest
B390	16-18	1.3	4-5	0.5	1.5	-	0.1	Rest
C443	4.5-6	2	0.6	0.35	0.5	0.5	0.15	Rest

2.3 Engine Specifications

Engine specifications were being taken from the journal of A. Raj Kumar et al [1]. The engine considered is a four stroke high speed SI engine, these type of engines are generally used in two wheelers. The specification is as follows:-

Table 2: Engine Specification

Engine Type	Four Stroke
Number of Cylinders	One
Displacement	150 CC
Expected Speed	6000 rpm
Cylinder bore	60 mm
Stroke	53 mm
Compression ratio	9
Clearance Volume	18.75cm^3
Piston area	28.2743cm^2
Inlet Port area	8.4823cm^2
Outlet Port area	7.0686cm^2
Delivery ratio, RCC	1.5
Scavenging Efficiency	77.6%
Fin thickness	2 mm

3. Results and Discussion

3.1 Temperature Distribution in the Cylinder Head for the Materials (A380)

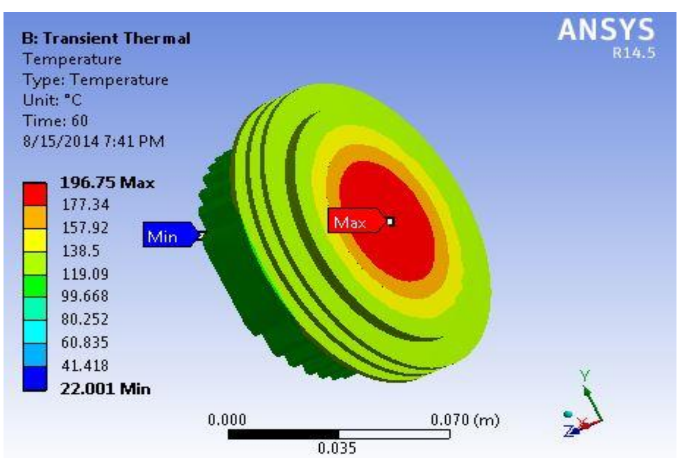

Figure 3: Temperature distribution obtained in the cylinder head at the end of 60 sec

The maximum temperature was 196.75^{0}C. Temperature distribution obtained in the cylinder head at the end of 60 sec for the material B390.The temperature at the ends of 60 sec was 177.3^{0}C

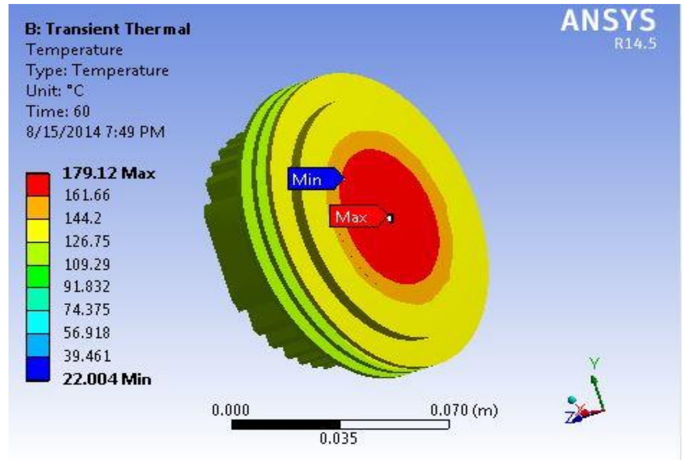

Figure 4: Temperature variation with Time for B390

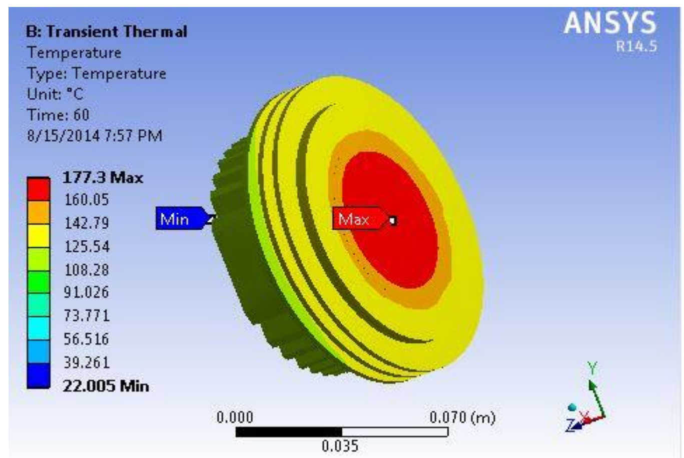

Figure 5: Temperature variation with Time for C443

The maximum temperature rose to 177.3^{0}C at end of the 60 sec

3.2 Stress Variation in the Cylinder Head with Time for A380 (Von Mieses)

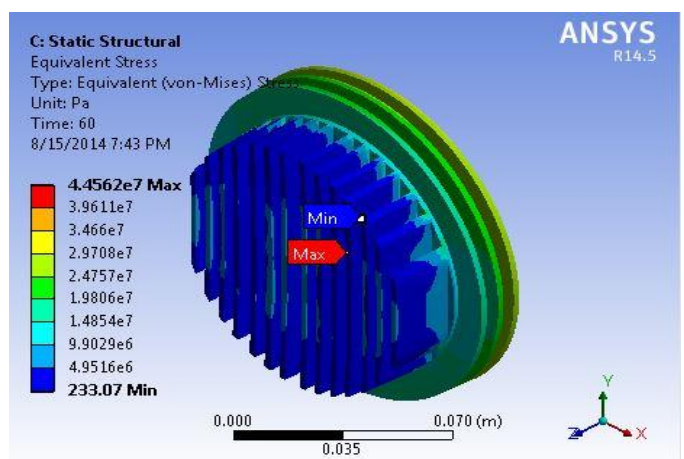

Figure 6: Stress variation with Time for A380

The maximum value of the thermal stress generated at the end of 60 sec was 44.56 MPa. The stress generated were well within the ultimate strength limit

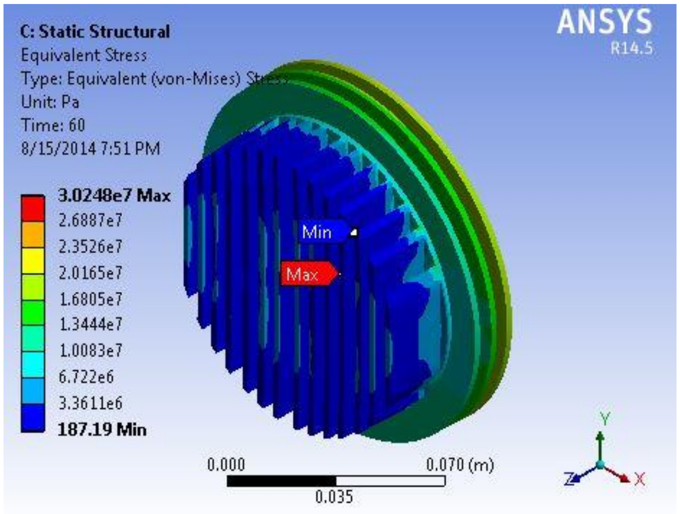

Figure 7: Stress variation with Time for B390

The maximum thermal stress generated at the end of 60 sec was 30.24 MPa, the minimum stress generated at the end of 60 sec is 187.19 pa.

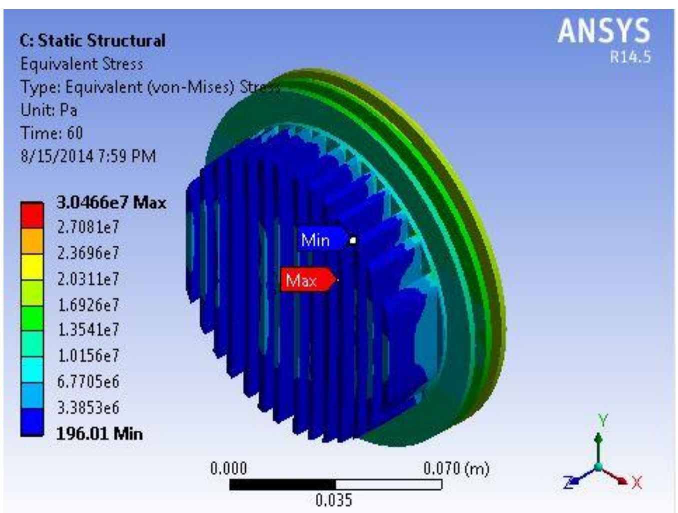

Figure 8: Temperature variation with Time for C443

The maximum stress generated at the end of 60 sec was 30.46 Mpa and the minimum stress generated at the end of 60 sec was 196.01 pa. This value of stress is marginally higher than B390

3.3 Thermal Strain variation in the Cylinder Head with Time for A380

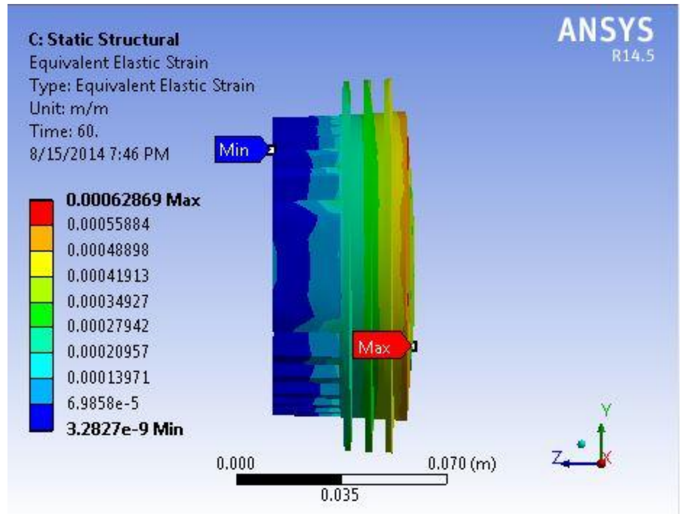

Figure 9: Thermal Strain variation with Time for A380

The maximum value of thermal strain that occurred for A380 at 60 second was 0.00058756 m/m which was highest among all the materials

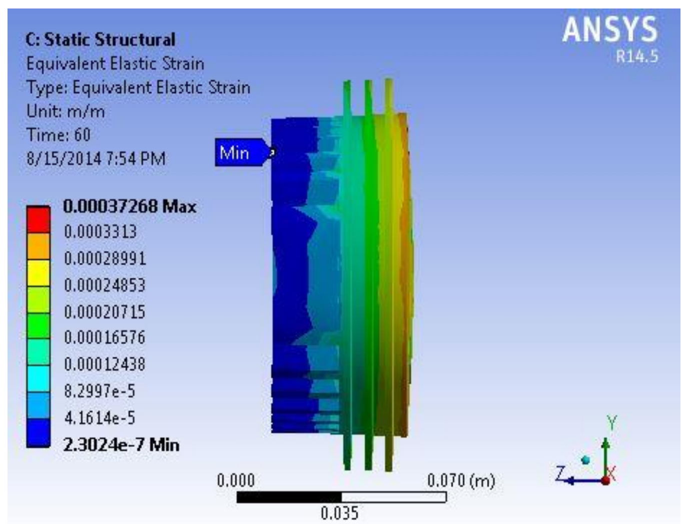

Figure 10: Variation of Thermal Strain with time for the material B390

The maximum magnitude of thermal strain developed in B390 is 0.0003483. Since the coefficient of thermal expansion is lower in case of B390.

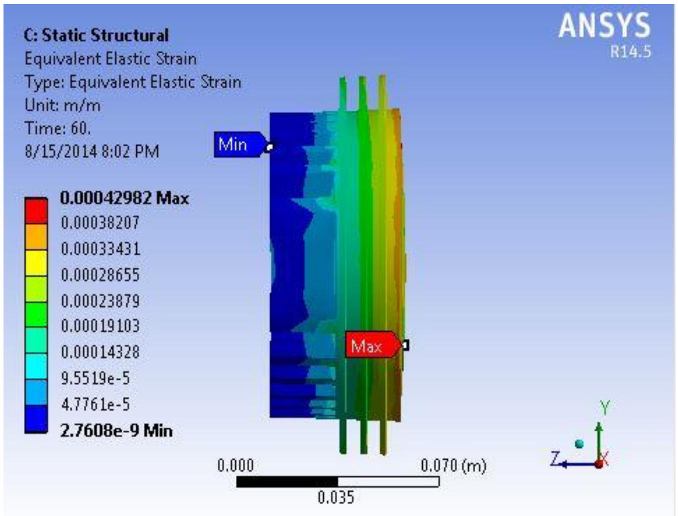

Figure 11: Strain variation with Time for C443

The magnitude of thermal strain is higher for C443 than B390 because the coefficient of thermal expansion of C443 is highest among the three hence the magnitude of strain is also high.

4. Conclusions

- The temperature distribution in the cylinder head for the material A380 has higher thermal gradient than for the material C443 and B390. The difference between maximum and minimum temperature for A380 is about 96.51 0C while for B390 and C443 is 72.16 and. 68.710C which means B390 and C443 offers more uniform temperature distribution than A380, as there thermal conductivity is higher therefore they will reach steady state earlier than A380.
- The magnitude of the strain for the material A380 is 0.000628 which was highest among all the three materials. However the maximum value of thermal strain for the material C443 was 0.0004298 which was higher than B390, 0.0003727, this is because coefficient of thermal expansion of C443 is higher than B390 that is why strain developed in C443 is higher than B390 even though the temperature developed in B390 are higher than C443.The maximum thermal stress obtained in the cylinder head in case of A380 is 44.56 Mpa while for B390 and C443 was 30.24 Mpa and 30.46 Mpa which is much less than A380. The stresses generated in C443 is marginally higher than B390 this is because C443 has higher elastic modulus than B390. The values of stresses are well within the safety limit. The graphs of maximum and minimum temperature variation with time shows same temperature variation characteristics for all the three materials and so the stress and strain graph, which means temperature and stress variation pattern are same for all the materials. From the following analysis it is evident that B390 and C443 are better alternative for the cylinder head and engine for the purpose of heat transfer.
- Cylinder head was analyzed for different fin thickness which were 2mm, 2.5mm, 3mm and 3.5m„m. It was observed that as the fin thickness was increased the temperature of the cylinder head falls. The minimum value of cylinder head temperature was 149.8^{0}C for C443 and fin thickness 3.5 mm.

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