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Temperature transients of piston of a Camless S.I Engine using different combustion boundary condition treatments

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Abstract

Simplified finite element model of spark ignition (SI) engine to analyse combustion heat transfer is presented. The model was discredited with 3D thermal elements of global length 5 mm. The fuel type is petrol. Internal nodal temperature of cylinder body is defined as 21000C to represent occurrence of gasoline combustion. Material information and isotropic material properties are taken from published report. The heat transfer analysis is done for the instant of combustion. The model is validated by comparing the computed maximum temperature at the piston surface with the published result. The computed temperature gradient at the crucial parts are plotted and discussed. It has been found that the critical top surface suffered from thermal and the materials used to construct the engine parts strongly influenced the temperature distribution in the engine. The model is capable to analyze heat transfer in the engine reasonably and efficiently.

Key words : Piston, Boundary conditions, Thermal analysis, NASTRAN etc.

1. Introduction

Engine pistons are one of the most complex components among all automotive or other industry field components. The engine can be called the heart of a car and the piston may be considered the most important part ofan engine. There are lots of research works proposing, for engine pistons, new geometries, materials and manufacturing techniques, and this evolution has undergone with a continuous improvement over the last decades and required thorough examination of the smallest details. Notwithstanding all these studies, there are a huge number of damaged pistons. Damage mechanisms have different origins and are mainly wear, temperature, and fatigue related. Among the fatigue damages, thermal fatigue and mechanical fatigue, either at room or at high temperature, play a prominent role.

This work is concerned only with the analysis of fatigue-damaged pistons. Pistons from petrol and diesel engines, from automobiles, motorcycles and trains all suffers from damage. Damages initiated at the crown, ring grooves, pin holes and skirt are assessed. A compendium of case studies of fatigue-damaged pistons is presented. An analysis of both thermal fatigue and mechanical fatigue damages is presented and analysed in this work.

Piston materials and designs have evolved over the years and will continue to do so until fuel cells, exotic batteries or something else makes the internal combustion engines obsolete. The main reason of this continuous effort of evolution is based on the

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fact that the piston may be considered the heart of an engine. The piston is one of the most stressed components of an entire vehicle pressures at the combustion chamber may reach about 180–200 bar [1] a few years ago this value was common only for heavy-duty trucks but nowadays it is usual in HDSI engines. Speeds reach about 25 m/s and temperatures at the piston crown may reach about 4000C[1]. As one of the major moving parts in the power-transmitting assembly, the piston must be so designed that it can withstand the extreme heat and pressure of combustion. Pistons must also be light enough to keep inertial loads on related parts to a minimum. The piston also aids in sealing the cylinder to prevent the escape of combustion gases. It also transmits heat to the cooling oil and some of the heat through the piston rings to the cylinder wall.

As one of the main components in an engine, pistons technological evolution is expected to continue and they are expected to be more and stronger, lighter, thinner and durable. The main reason is because the mechanical efficiency of an engine is still low and only about 25% of the original energy is used in brake power [2].One thing that has not changed is the basic function of the piston. The pistons form the bottom half of the combustion chamber and transmits the force of combustion through the wrist pin and connecting rod to the crankshaft. The basic design of the piston is still pretty much the same. So what has changed? – The operating environment. Today's engines run cleaner, work harder and run hotter than ever before. At the same time they are expected to last longer and with minimal maintenance. Developments have been achieved in different fields: examples may be found on the following papers of piston geometry/combustion

flow [3, 4]; materials/mechanical and thermal behaviour [5–8]; materials/wear and lubrication (coatings)[9–14]; analytical tools – FEA [15, 16]; processing technologies [17,18];etc. Notwithstanding this technological evolution there are still a significant number of damaged pistons.

Damages may have different origins: mechanical stresses; thermal stresses; wear mechanisms; temperature degradation, oxidation mechanisms; etc. In this work only mechanical damages and in particular fatigue damages will be assessed. Fatigue is a source of piston damages. Although, traditionally, piston damages are attributed to wear and lubrication sources, fatigue is responsible for a significant number of piston damages. And some damages where the main cause is attributed to wear and/or lubrication mechanisms may have in the root cause origin a fatigue crack. Fatigue exists when cyclic stresses/deformations occur in an area on a component. The cyclic stresses/deformations have mainly two origins: load and temperature. Traditional mechanical fatigue may be the main damaging mechanism in different parts of a piston depending on different factors. High temperature fatigue (which includes creep) is also present in some damaged pistons. Thermal fatigue and thermal –Mechanical fatigues are also present in other damaged pistons. For a better understanding of the damaging mechanism different analytical tools, such as finite element analysis, fractographic analysis, metallurgical analysis, etc., can be used whenever they are necessary for a clear understanding of the damaging mechanism. A finite element linear static analysis, using ‘‘cosmos works’’, is used for stress and temperature determination. Only aluminium pistons are assessed in this work because most of the engine pistons are in aluminium.

Literature Review: The finite element analysis is performed using CAD software to investigate and analyse thermal stress distribution at the real engine condition during combustion process. Piston skirt may appear deformation usually causes crack on the upper end of the piston head. Due to deformation, stress concentration is caused on the upper end of the piston and, the stress distribution on the piston mainly depends on the deformation of piston. Therefore piston crown should have enough stiffness to reduce the deformation.[19]The preliminary analyses presented in the paper was to compare the behaviour of the combustion engine piston made of different type of materials under thermal load[20]. Finite element analysis is used to analyse stresses in a piston of an internal combustion engine. The stresses due to combustion gas load only are considered so as to reduce the weight and hence to increase the power output of engine. [21] The distribution of the temperature on the top surface of the piston which predicts the top surface of the piston may be going to damaged or broken during the operating conditions. [22] The materials with high thermal conductivity is considered better than the material type of low thermal conductivity [23]

Since environmental impact from transport sector which mainly utilizes energy from combustion of fossil fuel awakened many people around the world, widespread global initiatives have taken place in the light of this awareness. The development of hybrid electric vehicles and solar cars is one example. The use of alternative fuels such as biofuel, hydrogen fuel cells, and nano energy are among others. However, investment in electric vehicles received failing mark. It is much more expensive than gasoline fuelled peers. All are under the subject of research to make them commercially viable. There are still much more to be done to resolve cost and performance issues with these initiatives [24]. Because the world economy is so far dependent on oil in a way that no other energy source can claim, improving SI engine performance still needs to pay attention.

Combustion occurs when the compressed mixture of air and fuel inside the cylinder is ignited by a heat source from a spark plug. The combustion temperature can be as high as 20000Cinonecycle.Suchahighandrepeatedthermaloperationveryoftencausesthefatiguefailureoftheenginecomponents[25]. In the past, many researchers had done the research on thermal analysis of SI engine using different approaches with the core objective of improving the engine performance. The analysis was mostly cantered on specific parts of the engine. Investigated in earlier work were the specific parts of the engine, particularly piston and combustion chamber. Thermal analysis of engine piston was reported in [26- 28]. In the report of [26], a quarter model of the piston was developed using finite element method to analyse its thermal behaviour. Symmetric thermal boundary conditions and simple combustion model for combustion side boundary condition were defined to the piston. The numerical results were well-matched with experiment. On the other hand, combustion boundary conditions were treated differently [27, 28] when carrying out the piston thermal analysis. In order to do so, a good interface that linked between NASTRAN and KIVA-3V finite element codes was developed. It was found that using spatial and time averaged combustion boundary condition was an effective way to analyse behaviour of the piston under thermal shock compared to surface and time averaged boundary condition.

Heat conduction in combustion chamber wall was modelled in [29] to simulate multidimensional combustion in SI engine. However, comprehensive study of combustion chamber wall was found in [30-32]. The study highlights the model validation, the grid optimization, and the effect of geometry and material on the wall temperature. The heat conduction between the engine body and other components were also extensively investigated using FEM. Finite element model of a cylinder structure with a twin-cam 16-valve was presented in [33]. They used the commercial FE code to predict thermal and stress/strain results at various loading conditions and operating environments. The structural analyses of a cylinder head under engine operating conditions were performed in [34,35] using finite element simulation. It was reported that the capacity of gasket sealing was principally dependent on the pre-stressing of the bolts, which was the source of the maximum external loading on the inner structure of the cylinder head. In addition, the location of the weakest contact pressure on the

Table 1. Parameters required for designing of piston are:

Piston Specification	
Mass of Piston	0.400 kg
Mass of Conn Rod	0.30 kg
Crankpin Mass	0.12 kg
Crank Radius	39.5 kg
Reciprocating Mass	0.600 kg
Cylinder Pitch	30.0 mm
Weight of Flywheel	1.00 kg
Rotating Mass	0.600 kg

Engine Specifications	
Power	1Kw
Torque	40Nm@1750rpm
Speed	4000rpm
Other data	
Stroke length	55mm
Engine Type	S.I Engine
Comp Ratio	10:6

raised portion of the gasket can be transferred as a result of the effect of thermal stress/strain. Furthermore, reported in [35] was the effect of fuel and engine operational characteristics on the heat loss from combustion chamber surfaces of SI engines. Important information was also found in [36][41] which stated that the highest temperature of any point in each component must not go more than 66% of the melting point temperature of the component material. Recently, computational fluid dynamics technique was applied to simulate heat transfer and combustion in a four-stroke single cylinder engine [37]. The engine geometry was made up with pent roof combustion chamber geometry, having two inlet valves and two exhaust valves. It was reported that the local value of heat transfer coefficient had equivalent trend with crank angle, and numerical computation was an appropriate tool to study heat transfer in a SI engine in comparison with available experimental correlations.

A two zone combustion model with zero-dimension was presented in [19] to simulate the transient processes in a two-stroke SI engine. A unique feature of their model was a spherically expanding flame front originating from the spark location incorporated in network model. The model is numerically solved using the network simulation technique adopted from electrical circuit resolution. Simulation results showed that the most critical point of the engine was in the spark plug and its vicinity.

Problem Statement: The function of the piston is to absorb the energy released after the combustion and to produce useful mechanical energy. 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. The investigations indicate that the greatest stress appears on the upper end of the piston and stress concentration is one of the main reasons for fatigue failure. Due to stress concentration and high thermal load the upper end of the piston, crack generally appears. This crack may even split the piston. The main objectives are i) To investigate the maximum stress using stress analysis ii) to investigate the maximum temperature using thermal analysis. iii) To investigate Stiffness of the piston crown to reduce the deformation. See Table 1.for various parameters required for designing of piston.

2. Methodology

Finite element model of the gasoline SI engine was developed in general-purpose FE code [39]. The model was simplified into 2D geometry with its computational domain comprising one cylinder and its major components including combustion chamber, water jacket, piston head, cylinder head with inlet/outlet manifolds, and intake/exhaust valves. The dimensions and materials of all parts were based on the actual engine of a passenger car. Table 2.shows typical materials used for the engine parts [27, 40]. The properties of these materials

Table 2. shows typical materials used for the engine parts [27, 40]

Engine Components	
Cylinder head	Aluminum2024-T6
Cylinder block	Aluminum 2024-O
Intake/Ex. Valve	AISI 1010 Steel
Piston	Aluminum A380-F

were available inside the FE package [39] used.

All parts were discredited except the water jacket as the presence of water cooling would be defined in boundary condition later. Despite simplification of the model, model discretization took times to complete due to the presence of irregular geometries and very small elements. Feasible element size of 0.001 was chosen through trial-meshing. Total number of elements was 24921. Currently, isotropic material properties were assumed. The initial temperature for each part in the engine was assigned as 270℃ assuming it was at room temperature before combustion. The presence of water coolant was modelled by assigning convection coefficient of water on all surfaces of water jacket. In order to represent the combustion occurrence, nodal temperatures inside the cylinder and combustion chamber were defined to be 1100℃. Transient heat transfer analysis was performed to predict temperature distribution through each part. Since the analysis was done at the instant of combustion only, the analysis time was set to be 0.12 s to be consistent with the actual combustion period.

Governing equations for two-dimensional conduction with convection can be expressed as follows. The temperature distribution T(x, y, t) is dependent on both position and time. The differential equation governing the temperature distribution across the cylinder wall is

$$k\ \delta^2T/\delta x^2+k\delta^2T/\delta y^2=c\rho\delta T/\delta t+2h(T-T_a) \quad (1)$$

where c and ρ denote material specific heat and density respectively.

For 4-node 2D element, temperature distribution in the element is described as

$$T(x,y,t)=\sum_{i=1}^{4}N_i(x,y)T_i(t) \quad (2)$$

where Ni(x,y) is the interpolation function associated with nodal temperature Ti (t). Subsequently, finite element formulation can be written as:

$$\iint_A k\ (\delta T/\delta x.\ \delta N_i/\ \delta x+\ \delta T/\delta y\ .\delta N_i/\ \delta y)dA+2h\iint_A TN_i dA =2hT_a\iint_A N_i\ d\ A\ +\ c\rho\iint_A \delta T/\delta t\ N_i\ d\ A \quad (3)$$

which has the following general form on the element,

$$[Ce][Te]+[Ke][Te]=[fhe]+[fhse] \quad (4)$$

Which has the following general form on the element, and on the assembly is,

$$[C][T]\ +\ [K]\ [T]\ =\ [fh]+[fhs] \quad (5)$$

where [c, C] and [k, K] are conductive matrix and mass matrix for element and assembly respectively, and fh, fhs, and fh, fhsare element and global conduction and convection terms respectively. Finite element equation was solved by forward difference method. If the nodal temperature is known at time t and the forcing functions are evaluated at time t, “Eq. (5)” is solved algebraically for the nodal temperature at time (t + δt) where δt is time step. The work was done in two stages

1. Pre-Processing
2. Post-processing

Thermal Analysis of piston is done using finite element analysis software in order to determine the overall performance of the piston under various thermal loads acting on the piston during the various stages of combustion. The picture of a cam less engine piston is shown below:

Pre-Processing : Inpre processing various boundary conditions are applied in order to replicate

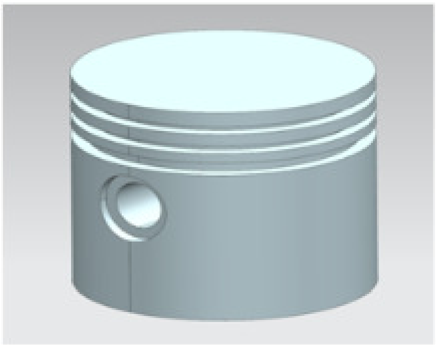

Fig. 1. A Camless Engine Piston

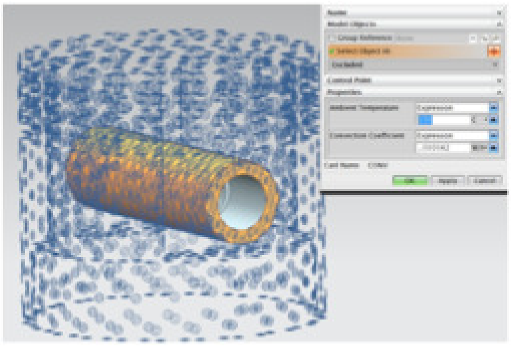

Fig. 2. Pre Processing (1)

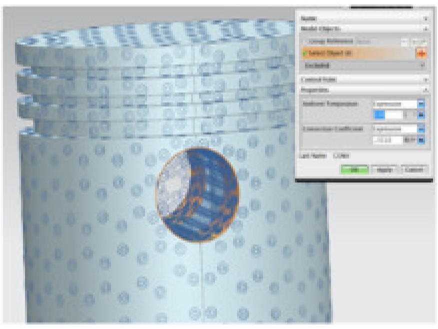

Fig. 3. Pre Processing (2)

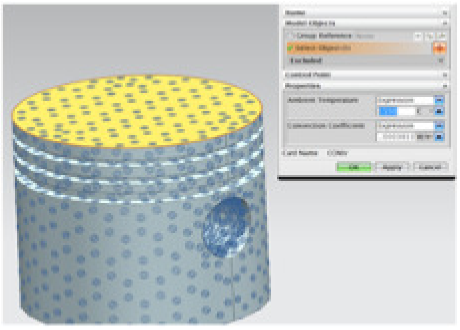

Fig. 4. Pre Processing (3)

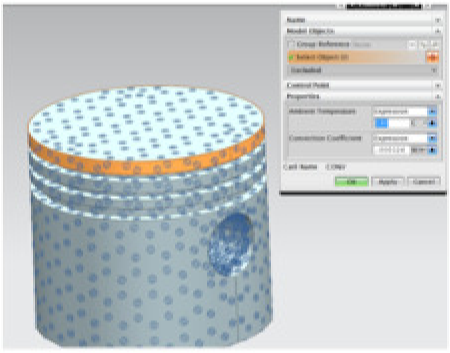

Fig. 5. Pre Processing (4)

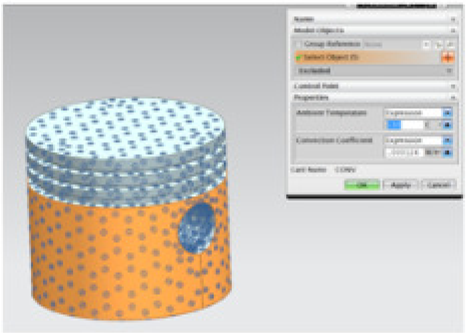

Fig. 6. Pre Processing (5)

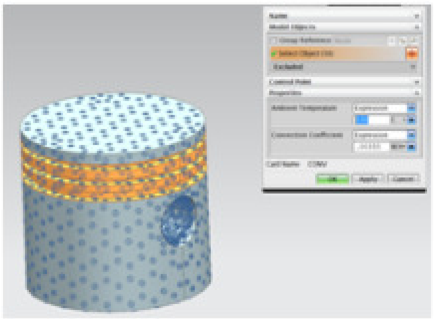

Fig. 7. Pre Processing (6)

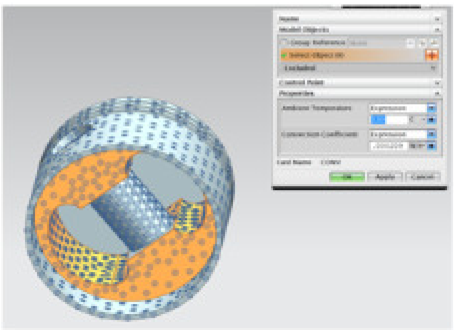

Fig. 8. Pre Processing (7)

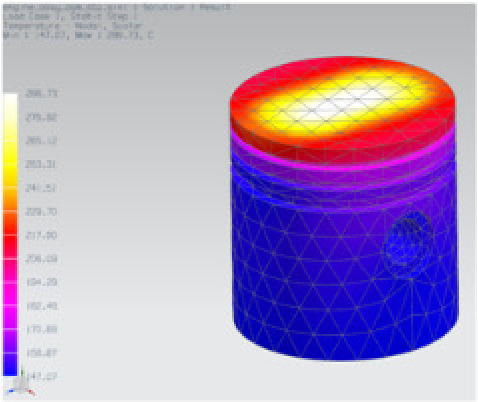

Fig. 9. Temperature Flow

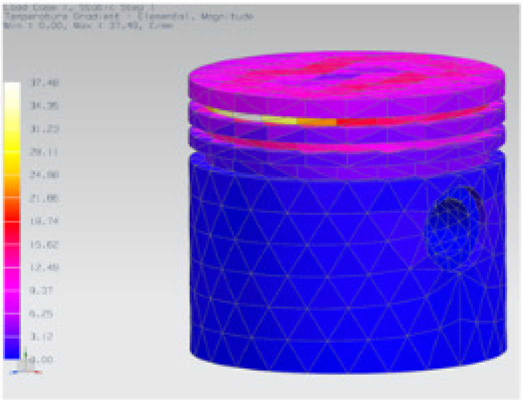

Fig. 10. Temperature Gradient

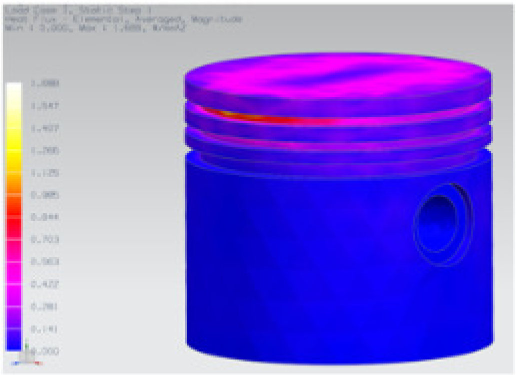

Fig. 11. Heat Flux

the actual environment during the combustion.

3. Conclusion

Since the temperature value is 1300C which is in the optimum range of piston working temperature therfore the piston survies the thermal load test using FEA.In this study, the wok is carried out to measure the distribution of the temperature on the top surface of the piston. Which predicts that due to temperature weather the top surface of the piston may be going to damaged or broken during the operating conditions because damaged or broken parts are so expensive to replace and generally are not easily available. So it is possible to recover the damage or broken parts due to thermal analysis before taking into operations. It can be seen from that the prescribed operating temperature inside the cylinder penetrates the piston crown through nearly 70 % of its thickness before piston ring dissipates some of heat.

Figure 1- CAD Model of piston.
Figure 2 - Boundary condition to define ambient temperature of 130 C and convection coefficient of .0016 W/mm2 C is applied on the pin resting area on piston.
Figure 3 - Boundary condition to define ambient temperature of 150 C and convection coefficient of .000042 W/mm2 C is applied on the pin surface area .
Figure 4 - Boundary condition to define ambient temperature of 1100 C and convection coefficient of .0003810 W/mm2 C is applied on the piston top face.
Figure 5 - Boundary condition to define ambient temperature of 130 C and convection coefficient of .0003810 W/mm2 C is applied on the piston face as indicated
Figure 6 - Boundary condition to define ambient temperature of 130 C and convection coefficient of .0003810 W/mm2 C is applied on the piston face as indicated
Figure 7 - Boundary condition to define ambient temperature of 130 C and convection coefficient of .00355W/mm2 C is applied on the piston face as indicated

Figure 8 - Boundary condition to define ambient temperature of 130 C and convection coefficient of .000209 W/mm2 C is applied on the piston face as indicated

Figure 9 - This figure shows temperature flow pattern in the piston thereby indicating the flow of heat in the piston due to its shape and material properties.

Figure 10 - This figure shows temperature gradient in the piston

Figure 11 - This figure shows heat flux in the piston during the flow of heat in the piston .

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