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Heat Transfer Analysis in Internal Combustion Engine Piston Using Comsol Multiphysics: A Case Study of Tri-Cycle

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Abstract: The transient nature of heat flowing involving more than single variable, complicated method of measuring temperature across the length of the liner and ambiguous boundary conditions pose serious problems for the analysis of heat transfer rate on the piston of an internal combustion engine using FEM (Finite Element Method). This present study analyzed the heat transfer rate on the piston of a Tri-cycle engine. The studied piston was selected based on its applications in automobile and other engineering applications. The analysis was basically on the transient state forced-convection and conduction heat transfer. As initial condition, the temperature distributions were considered along the piston at a range of 523K – 673K. The parameter used for the simulation were liquid (Gasoline), Gases (Air) and Aluminium silicon UNSA96061 (Piston). The modeling and simulation were performed by using COMSOL-Multiphysics 4.3a software. The mesh optimization was undertaken by using FEM techniques to predict the maximum and mimimum temperature on the piston at every stages of simulation with time dependent. It was discovered that the temperature along the piston of the try-cycle varies with respect to time. The transient analysis revealed that the temperature of the piston at the TDC (Top Dead Center) in the first power stroke is higher compare to the subsequent power strokes, which is an indication that more heat is transfer at subsequent power strokes. Probable recommendations were later made.

Keywords: Tri-cycle, Piston, FEM, Comsol, Heat transfer.

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1 INTRODUCTION

Energy conservation and efficiency have always been the quest of engineers concerned with IC engines. The knowledge of temperature distribution in the piston and liner of a petrol engine is of immense use to the designer for calculating the fatigue strength, thermal stresses and achieving higher output [1]. According to Faghri et al [2], heat and mass transfer or transport phenomena can be encountered in many applications ranging from design and optimization of traditional engineering systems, such as heat exchanger, turbine, electronic cooling [3], heat pipes, and food processing equipment, to emerging technologies in sustainable energy, biological systems, security, information technology and nanotechnology.

However engine pistons as a component of reciprocating IC-engines are one of the most complex components among all automotive and other industry field components. The engine can be called the heart of a vehicle and the piston may be considered the most important part of an 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 [4]. Thus, in order to have full understanding of phenomenon of heat flow through the piston and liner, the temperature distribution within the piston and liner will come handy for designers. The transient nature of heat flow involving more than single variable, complicated method of measuring temperature across the length of the liner and ambiguous boundary conditions pose serious problems for the analysis of heat flow through the piston and liner of a petrol engine [1]. Invariably, piston as one of the most critical components of an engine must be designed to withstand the damage that is caused due to extreme heat and pressure of combustion process. The value of stress that caused the damages can be determined by using FEA [5].

Thus, this work will focus on temperature distribution and heat transfer rate which are of much importance especially in SI engines. Due to practical difficulties involved in measuring temperature and heat transfer rates in different locations of piston and liner, it is necessary to adopt analytical and numerical methods for evaluating heat transfer rates through the piston and liner under varying conditions of engine. This present study is aimed at analyzing the heat transfer rate of an internal combustion engines piston using finite element methods (FEM). This would be achieved by formulating a model for analyzing the convective heat transfer rate of an internal combustion engines piston as well as simulate the obtained results using COMSOL- Multiphysics.

2 METHODOLOGY

The two parameters considered were combustion chamber temperature and the atmospheric temperature. These are required to know the rate of heat transfer at different levels of such parameters. A Tri-cycle under regular maintenance was used for the experimental analysis, in order to obtain very accurate results. Since the experimental test was carried out in the auto-workshop outside the institution, a special stand connector like the temperature measurement apparatus could not be easily obtained but an alternate method was later used. The tri-cycle engine used was a 2-stroke, single cylinder spark Ignition engine, In-line, air- cooled type. The temperature measuring device used was thermocouple and the experimental aspect of the study was carried out on the test bed.

Table 2.1: Prototype Piston Geometrical Information

1	Bore	80mm
2	Stroke	120mm

2.1 Analysis

The software package used for the analysis was the COMSOL Multiphysics 4.3. As a powerful finite element (FEM) and partial differential equation (PDE) solution engine, the software has ten (10) add-on modules that expand the capabilities in the following application areas:

i. AC/DC Module
ii. Acoustics Module
iii. Chemical Species and Transport Module
iv. Electrochemistry
v. Fluid flow
vi. Heat transfer
vii. Plasma
viii. Radio Frequency (RF)
ix. Structural Mechanics
x. Mathematics

The heat transfer add-on module was used for the model simulation and analysis

2.2 Heat Transfer Analysis Analysis on the Model in COMSOL Multiphysics 4.3a

3D model of piston was imported into the COMSOL Multiphysics for preprocessing. Preprocessing of model consists of the following:

2.2.1 Selection of Physics

The problem studied was 3-D, transient and time dependent heat transfer problems.

2.2.2 Geometry

The piston was designed using AutoCAD software and later converted to ipt model using Autodesk INVENTOR and the model was later simulated using COMSOL Multiphysics. Heat is transferred by conduction through the wall of the cylinder into the piston, where there is air-fuel mixture and released by convection to the wall of the cylinder, conducted through the wall and radiate to the surrounding. The flow is assumed to be laminar, transient and incompressible.

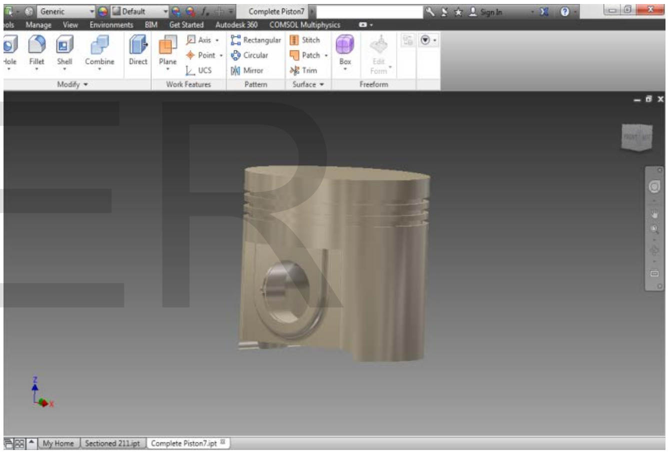

Fig. 2.1: Piston Model

2.2.3 Material Selection and Properties

Aluminium alloy 6061 (UNS A96061), gasoline (petrol) and air were selected on the material browser and the values of the selected parameters were supplied on the material content.

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Table 2.2: Material Contents of Air

Property	Name	Value	Units	Properties group
Ratio of specific heats	A	1.4	1	Basic
Heat capacity at constant pressure	c_p	1006	J/(kg*k)	Basic
Density	P	1290	Kg/m^3	Basic
Thermal conductivity	K	262	W/(m*k)	Basic
Dynamic Viscosity	M	0.0000 1697	Pa*s	Basic
Electrical Conductivity	σ	300	S/m	Basic
Speed of Sound	c	0.3	m/s	Basic

Table 2.3: Material Contents of Aluminium 6061 Alloy

Property	Name	Value	Units	Properties group
Dl	dL	5		Basic
CTE	CTE	2430		Basic
Thermal conductivity	K	167	W/(m*k)	Basic
Resistivity	Res	0.0000 000399	Ω*m	Basic
Coefficient of thermal expansion	alpha	0.0234	1/k	Basic
Heat capacity at constant pressure	Cp	936		Basic
Mu	Mu	0.0000 0296		Basic
Electrical conductivity	sigma	45	s/m	Basic
Density	Rho	2700	Kg/m*3	Basic
Kappa	kappa	1		Basic
Ratio of specific heats	gamma	1.4	1	Basic

Table 2.4: Material Contents of Gasoline

Property	Name	Value	Units	Properties group
Dynamic Viscosity	Mu	0.0262	Pa*s	Basic
Heat capacity at constant pressure	Cp	1008	J/(kg*k)	Basic
Density	Rho	1050	Kg/m^3	Basic
Thermal conductivity	K	520	W/(m*k)	Basic

2.2.4 Parametric Studies (governing equations and boundary conditions)

A) Heat transfer in fluids (ht):

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \boldsymbol{U} \cdot \nabla T = \nabla \cdot (K \nabla T) + Q + Q_{vh} + W_p \quad (2.1)$$

B) Heat transfer in solids (ht):

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \boldsymbol{U} \cdot \nabla T = \nabla \cdot (K \nabla T) + Q \quad (2.2)$$

C) Convective Cooling:

$$-n \cdot (-K \nabla T) = h \cdot (T_{ext} - T) \quad (2.3)$$

2.2.5 Meshing

The mesh chosen was Free Tetrahedral. The Completed mesh consists of 86225 elements and the number of degrees of freedom solved for was 18553 in 367 s. (6 minutes, 7 seconds).

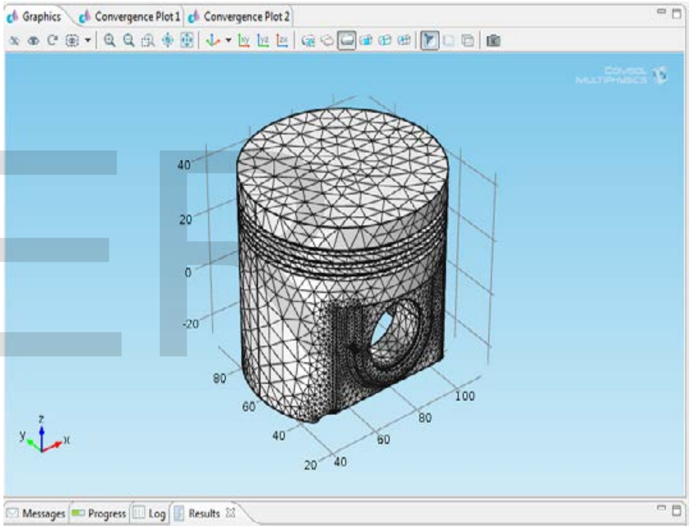

Fig. 2.2: Piston Mesh

2.2.6 Study:

In the Model Builder window, a time dependent study was chosen at a range of '0, 0.1, 10', in the edit field, before all temperature (ht) plot was updated at a time discrete solver. The study was later computed for post processing and visualization.

2.3: Model-Post-processing and Visualization

In post processing mode different plots types were obtained from sets of selected parameters. The solution variables were later visualized using the post processing utilities using their derivatives, and the space coordinates. Many frequently used expressions are predefined as application mode variables, directly available from lists in the Plot Parameters.

3 RESULTS AND DISCUSSION

The obtained simulated results from the COMSOL Multiphysics are presented below:

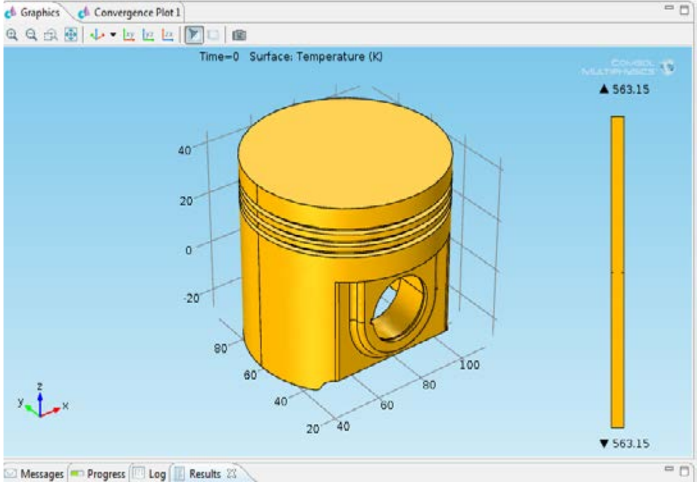

Fig. 3.1: Heat transfer in 0 second at 563.15K

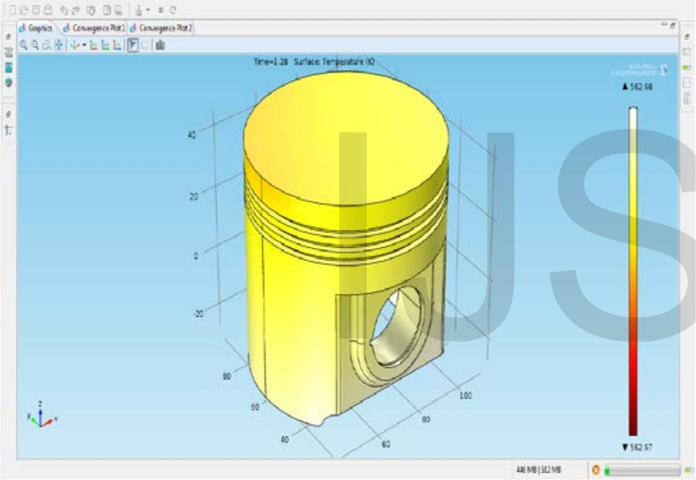

Figure 3.2: Heat transfer in 1.28 minutes

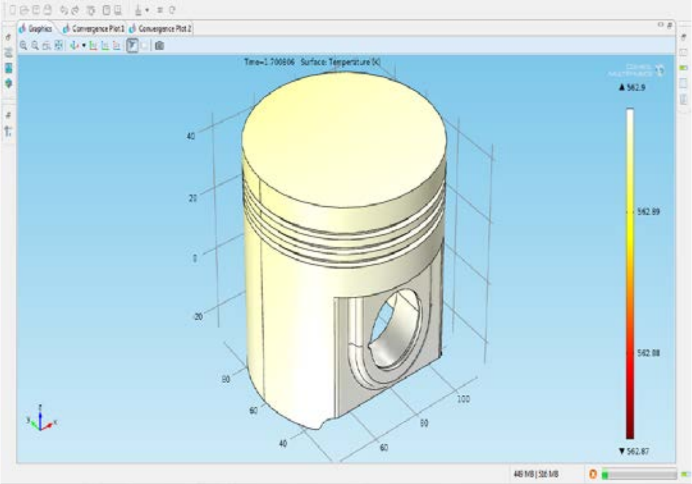

Figure 3.3: Heat transfer in 1.7 minutes

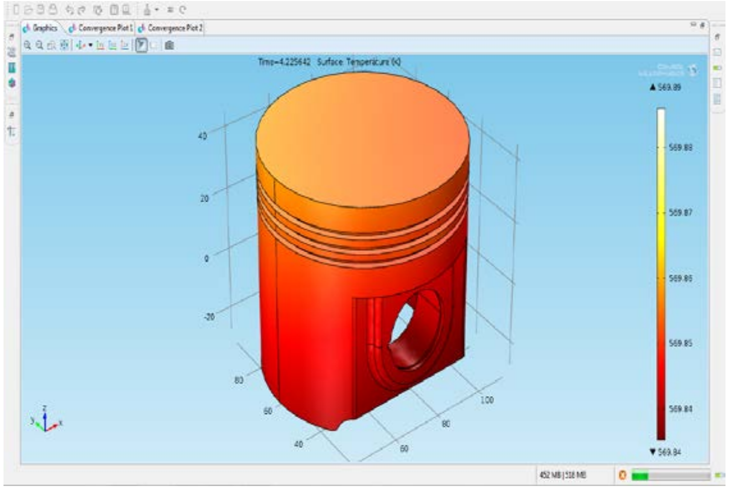

Figure 3.4: Heat transfer in 4.22 minutes

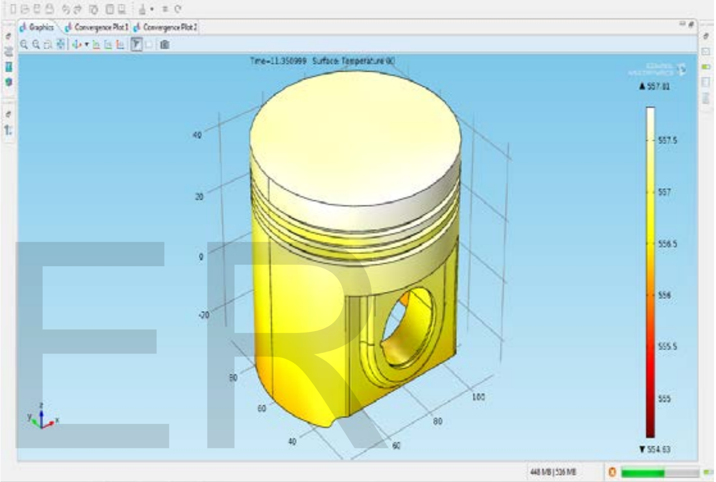

Figure 3.5: Heat transfer in 11.35 minutes

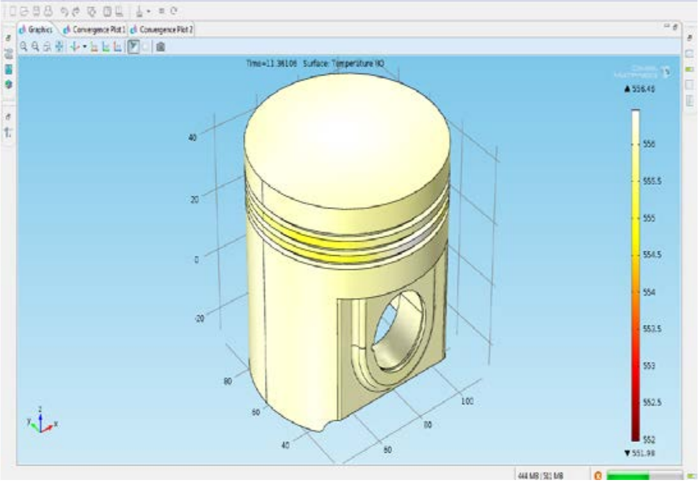

Figure 3.6: Heat transfer in 11.36 minutes

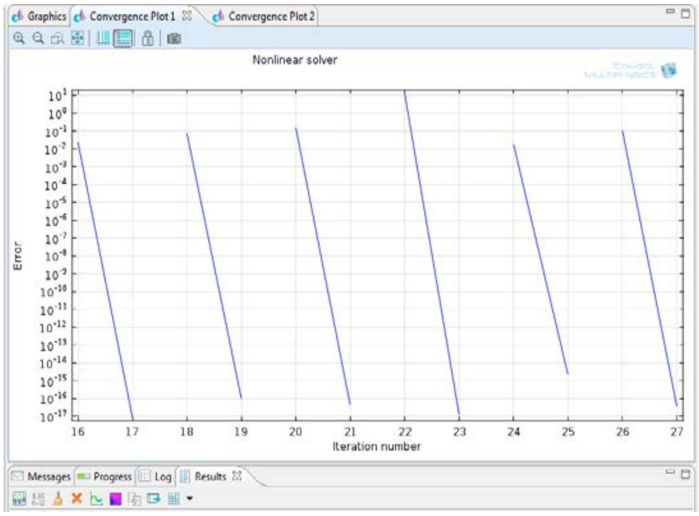

Figure 3.7: Non-Linear Solver

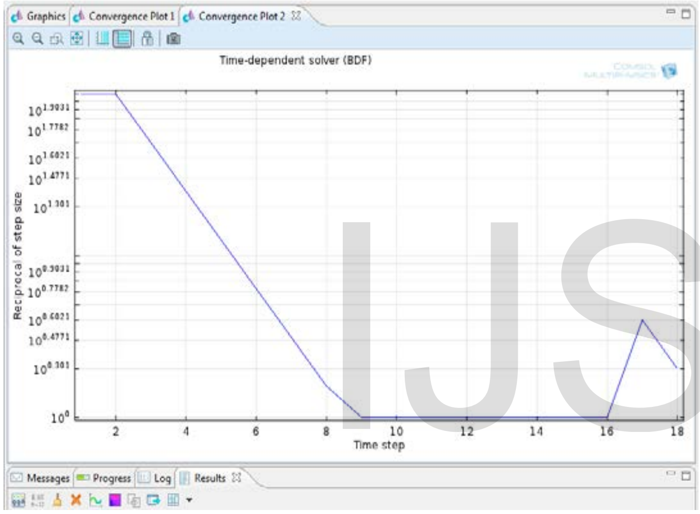

Figure 3.8: Time Dependent Solver

3.1: Discussion of Results

Fig. 3.1 shows the full piston model. The piston remains hot at 562.15K in 0 second. Heat transfer is yet to occur at this time.

Fig.3.2 shows the full piston model with the air-fuel mixture. Meanwhile the temperature of the piston has increased from 562.97K to 562.98K. Though, the increment is not significant since heat transfer is yet to take place at 1.28 minutes. At this time the percentage of fuel in the mixture is more compare to that of air.

Fig.3.3 shows the full piston model with more air intake in the mixture. Thus, the temperature of the piston has increased from 562.87K to 562.9K. More air has entered the inlet manifold while the piston is still at the BDC at 1.7 minute. Thus, the temperature distribution begins at this time.

Fig.3.4 shows the piston at TDC. At this point, the hot air-fuel mixture is ignited by the spark plug. This is term 'the power stroke'. Thus, the piston is red-hot and this is an indication that the temperature of the piston has increased from 562.9K to 569.89K. This is substantiated with the temperature gradient at 4.22 minutes.

From fig.3.5, the piston is returning to the BDC thereby given room to heat transfer to take place in 11.35 minutes. It was discovered that the temperature has reduced from 557.81K to 554.63K which shows that, there is still trace of heat at the lower power of the piston. This is an indication that the piston has not been completely transferred. 0.03K of temperature is yet to be transferred.

From fig.3.5, the piston has completely returned to the BDC thereby given room for heat to fully transfer in 11.36 minutes. It was discovered that the temperature has reduced from 557.81K to 554.63K which shows that, there is no trace of heat at the lower power of the piston.

Fig.3.7 is the non-linear plot of the error against iteration number. The model was iterated in 27 times. The highest error of about $10^{1}$was observed when the result was on the 23rd iteration.

Fig. 3.8 shows the time dependent solver of the reciprocal of step size against time step. The highest reciprocal of step size was recorded when the time step is between 0 and 2. This is an indication that heat is yet to be transferred for the first 2 seconds. Between the time step of 2 and 9, there is a gradual fall in the reciprocal of step size; this indicates that heat transfer is taking place. That is, the piston is returning from TDC to BDC. Between the step size of 9 and 16, the reciprocal of step size recorded the least constant value. This indicates that the piston is at the BDC and heat has been completely transferred. At the same time, this is the period at which more air-fuel mixture comes in. Thus, another cycle of heat transfer has occurred between 16 and 18 time-step. The first cycle recorded the highest reciprocal of step size, this supports the proposition in that, the temperature of the piston head when the piston attains its first TDC is higher compare to the subsequent ones.

4 CONCLUSION AND RECOMMENDATION

Although there are many of experimental studies regarding the internal combustion engines process, but few numerical studies focused on 3-D heat transfer analysis on a gasoline piston model. The model for determining the rate of heat transfer has been formulated, FEM in-built in the COMSOL Multiphysics software was used to determine the temperature gradient of the piston model and the result has been simulated using COMSOL Multiphysics software itself. From the result obtained above it was discovered that the temperature in the combustion chamber of the tricycle engine varies with respect to time, along the piston. The maximum and minimum temperature concentration was indicated at each stages of heat transfer. In conclusion, the transient analysis revealed that the temperature of the piston at TDC in the initial or first power stroke is higher compare to the subsequent power strokes. This is an indication that in the subsequent power strokes more heat is transferred due to some factors like surrounding air, oil etc which contributes to cooling effect. Thus, advancement in technology leads to this research, for improvement and longevity in two stroke engine performance. The results obtained can be validated using other available software packages like ANSYS, ABAQUS, NASTRAN, MATLAB, J-ANALYZER used in simulating the heat transfer on the piston of an IC Engines.

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