Thermal Analysis of SI-Engine using Simplified Finite Element Model

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***Abstract*— Simplified finite element model of spark ignition (SI) engine to analyze combustion heat transfer is presented. The 2D model is made up with main features of engine including combustion chamber, valves, manifold, cylinder body, piston head and cooling jacket, all projected at the cross section of the cylinder. The model was discretized with 2D thermal elements of global length 0.001. The fuel type is gasoline. Internal nodal temperature of cylinder body is defined as 2100°C to represent occurrence of gasoline combustion. The presence of cooling is modeled by assigning convection coefficient on cooling jacket. Material information and isotropic material properties are taken from published report. The transient 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 component likely suffered from thermal fatigue was the exhaust port near the cylinder head 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.**

***Index Terms*—SI engine, finite element method, combustion, thermal analysis**

I. Introduction

THE automobile engines are major parts that contribute to means of transportation. Researchers in automotive field have emphasized on improvement of engine design since fuel economy and environmental impact from transportation become a global concern. Research focus, to name a few, include introducing new engine material, bio-fuel cell, spark-free operating, hybrid – engine, and electric engine. Methodology in these researches relies on huge amount of experimentations. Although the engine designs have been considerably improved, the fuel economy and environmental impact are still under the subject of research. One reason of being inefficient, high fuel consumption and pollution is that quarter of energy is wasted as heat. In this regard, knowledge of temperature distribution in the engine components is important to tackle the problem. [1 – 3].

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In the light of shortcomings in experimentation, researchers have turned their attention to apply computer-aided engineering tool such as finite element method (FEM) in the structural and thermal analysis of various engine components. Finite element method has been widely used for solving real world problems due to its capability of modeling complex geometries, incorporating a variety of deformation models and complex boundary conditions [4, 5].

The objective of this work is to develop a simplified computational model of a gasoline spark-ignition engine using finite element method with which heat transfer due to fuel combustion could be analyzed. The model geometry was constructed as end-viewed the projection of engine main components at the cross section of one cylinder. Despite simplification, the model maintains major features of engine such as, combustion chamber, valves, manifolds, cylinder body, piston head and even cooling jacket, which primarily interact with combustion heat as well as are primarily responsible for engine performance. The model would be useful to find out useful information such as the temperature distribution, localized temperature, critical part of the engine where thermal damage may occur and even improving engine component materials and design.

II. Related Literature

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 fueled 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 [1]. 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.

Figure 1 illustrates major parts of typical engine in which a park ignition (SI) system is utilized for combustion process of gasoline fuel. 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 2000°C in one cycle. Such a high and repeated thermal operation very often causes the fatigue failure of the engine components [6].

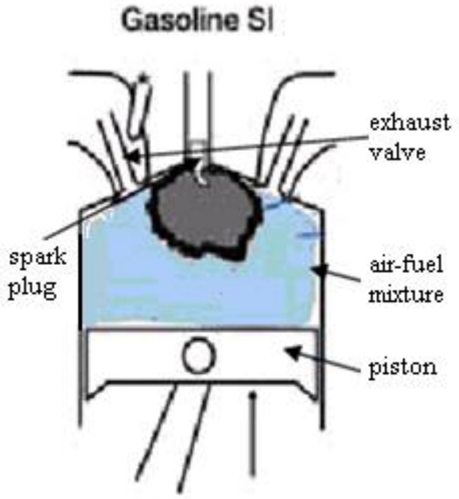

Figure 1. Schematic of spark-ignition system in vehicle engine [6].

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 centered 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 [7- 9]. In the report of [7], a quarter model of the piston was developed using finite element method to analyze its thermal behavior. 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 [8, 9] 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 analyze behavior of the piston under thermal shock compared to surface and time averaged boundary condition.

Heat conduction in combustion chamber wall was modeled in [10] to simulate multidimensional combustion in SI engine. However, comprehensive study of combustion chamber wall was found in [11-13]. 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 [14]. 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 [15, 16] 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 raised portion of the gasket can be transferred as a result of the effect of thermal stress/strain. Furthermore, reported in [16] 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 [17] 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 [18]. 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 cirruit resolution. Simulation results showed that the most critical point of the engine was in the spark plug and its vicinity.

III. METHODOLOGY

Finite element model of the gasoline SI engine was developed in general-purpose FE code [5]. 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 1 shows typical materials used for the engine parts [6, 20]. The properties of these materials were available inside the FE package [5] used.

TABLE 1.
MATERIALS USED FOR ENGINE COMPONENTS

Engine components	Materials
Cylinder head	Aluminum 2024-T6
Cylinder block	Aluminum 2024-O
Intake/exhaust valve	AISI 1010 Steel
Piston	Aluminum A380-F die casting alloy

All parts were discretized 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. Figure 2 illustrates complete FE model of the said engine. Currently, isotropic

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material properties were assumed. The initial temperature for each part in the engine was assigned as 27°C assuming it was at room temperature before combustion. The presence of water coolant was modeled 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 2100°C. And also the internal temperature of the exhaust manifold just behind the exhaust valve was defined as 2100°C assuming no significant temperature change between combustion period and exhaust valve opening. This exact figure was based on literature [6]. 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.

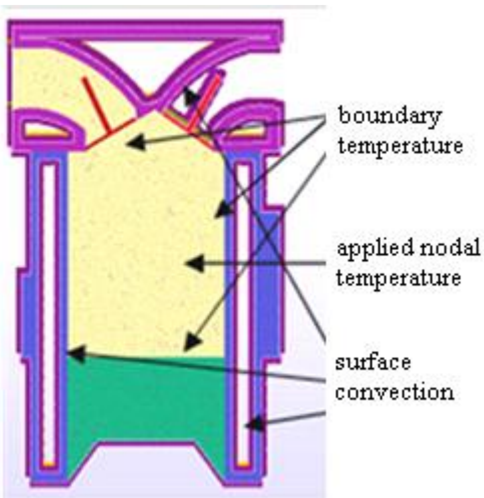

Figure 2. Finite Element model of SI Engine.

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

$$k\frac{\partial^2 T}{\partial x^2} + k\frac{\partial^2 T}{\partial y^2} = c\rho\frac{\partial T}{\partial t} + 2h(T - T_a) \qquad (1)$$

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

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

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

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

$$\iint_A k\left(\frac{\partial T}{\partial x}\frac{\partial N_i}{\partial x} + \frac{\partial T}{\partial y}\frac{\partial N_i}{\partial y}\right)dA + 2h\iint_A TN_i\, dA =$$

$$2hT_a\iint_A N_i\, dA + c\rho\iint_A \frac{\partial T}{\partial t}N_i\, dA \qquad (3)$$

which has the following general form on the element,

$$[C^e]\{\dot{T}^e\} + [k^{(e)}][T^e] = \{f_h^e\} + \{f_{hs}^e\} \qquad (4)$$

and on the assembly is,

$$[C]\{\dot{T}\} + [K]\{T\} = \{F_h\} + \{F_{hs}\} \qquad (5)$$

where [c, C] and [k, K] are conductive matrix and mass matrix for element and assembly respectively, and f_h, f_{hs}, and F_h, F_{hs} are 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, equation (5) is solved algebraically for the nodal temperature at time (t + Δt) where Δt is time step.

IV. Results and Discussion

Simplified finite element model of SI engine provides promising results. The computed results are comparable with published reports. Figure 3 depicts the computed overall temperature distribution across the engine components under consideration. The computed result was validated by comparing with the published result of [9] in which the piston surface temperature due to combustion was reported. The computed maximum temperature at the piston surface was about 220°C while that in the published data was 223°C. The percentage of error is only 1.37%. Therefore the computed results are acceptable.

Figure 4 shows the temperature gradient plotted for the node picked up at the exhaust valve surface (Refer to the contour plot shown together). After combustion had taken place, heat transfer from combustion to the exhaust valve surface causes its surface temperature reaches the maximum of 430°C.

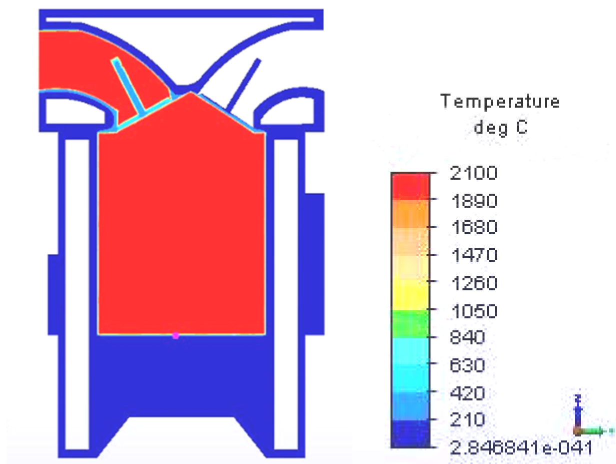

Figure 3. Overall temperature distribution.

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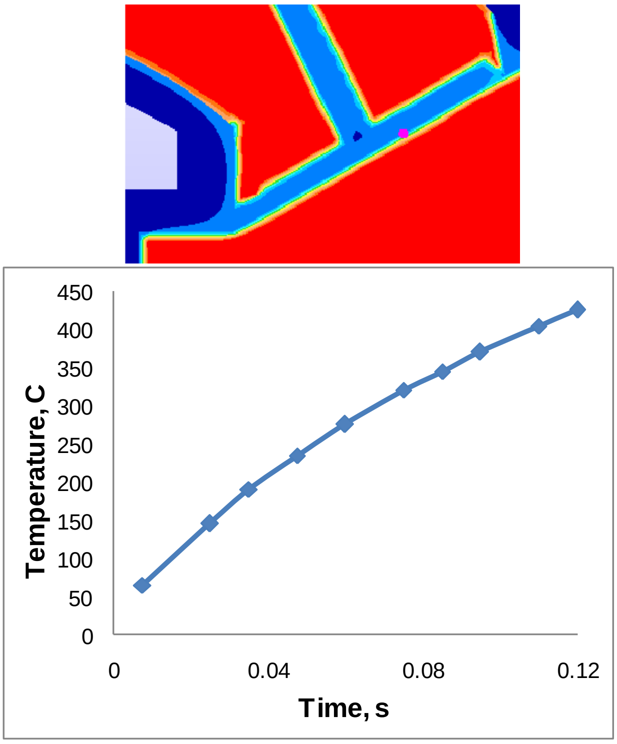

Figure 4. Temperature gradient at the exhaust valve surface.

The temperature gradient is strongly influenced by thermal properties of the material used. In other words, the use of material having high thermal resistance with high melting point is very important for the long life of the engine components working under severe conditions. From the computed results, it can be stated that the exhasut valve is still able to operate in high temperature region since according to the reports of [17], the maximum temperature of the valve is below its threshold value i.e. 66% of melting temparatuer of the valve material. It is also agreeable with the thermal strength of material stating the material can operate well in thermally-impacted environment [20].

Figure 5 shows the temperature gradient plotted for the node selected at the exhaust port surface, which directly meet the exhaust gas coming out of the cylinder after combustion. After combustion, the maximum temperature at this surface reaches about 310°C. Even though the temperature is not as high as that at the exhaust valve surface, the part may become in critical condition after certain time as the maximum temperature of the part is almost near to 66% of melting point of the part material. The critical part here can be described as the part that is subjected to thermal fatigue after being contact with combustion flame repeatedly.

Figure 6 shows the temperature gradient for the node chosen at the cylinder wall after combustion. The maximum temperature was found as 195°C. The result showed that the lowest maximum temperature occurred at the cylinder wall compared to other surrounding components that contact with combustion flame. The prominent effect of cooling was also evident. The result indicated the appropriateness of material used to construct cylinder wall as the oil-side surface of the cylinder wall must be kept below 200°C to prevent deterioration of the lubricating oil film. The deterioration of oil film problem is one of the factors that affects engine performance and efficiency.

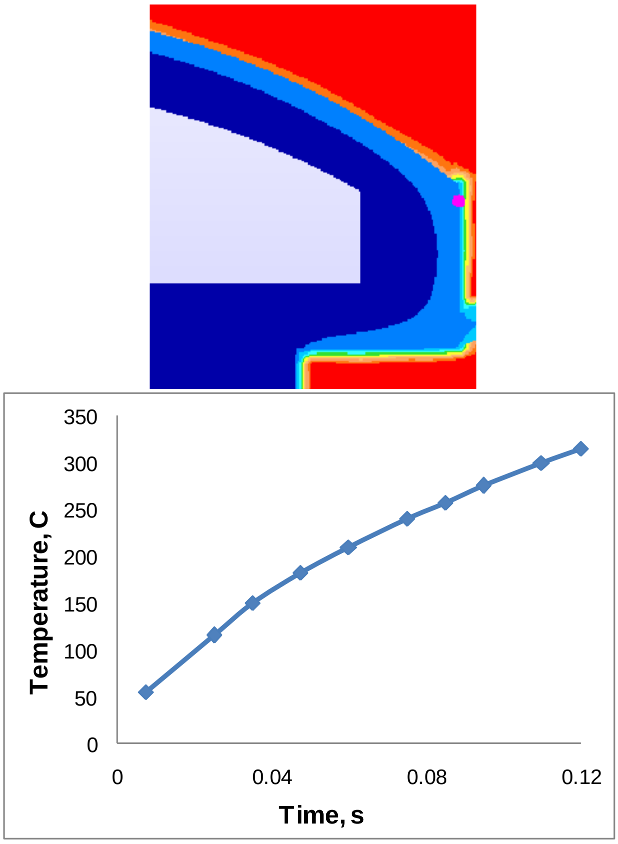

Figure 5. Temperature gradient at the exhaust port internal surface.

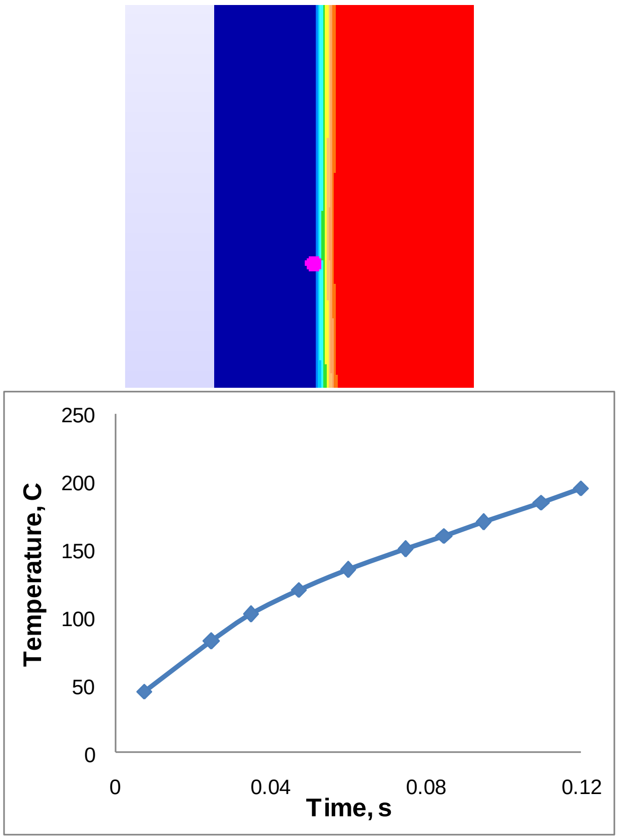

Figure 6. Temperature gradient at the cylinder wall.

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V. CONCLUSION

Finite element model of gasoline spark ignition engine has been successfully developed and simulated to analyze heat transfer during combustion process. The computational analysis had been carried out in order to obtain temperature distribution across the major engine components. The results of finite element analysis have been found to be in good agreement with the published report.

The finite element prediction has indicated that thermal effect in the combustion chamber is influenced by major parameters such as combustion flame temperature, convection of cooling system, and thermal properties of engine component materials. Apparently, the choice of material for part component in the combustion chamber is one of the solutions in order to improve engine performance and efficiency. In addition, the geometry and dimension of the engine parts also can be considered in order to improve the engine performance. The proposed model is simple, yet efficient to analyze thermal condition of the engine component during engine operation and even performance of engine, choice of suitable material improvement of component and design etc.

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