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Investigation of Multipoint Spark Ignition Engine Using CFD Code

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Author's contribution

The sole author designed, analyzed and interpreted and prepared the manuscript.

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ABSTRACT

The main aim of this research is to utilize the emerging combustion process technology in order to develop the combustion process inside spark internal combustion engine which is very important factor for engine performance and emissions, which will be achieved by better understanding of this process. For this purpose a simulation model will be developed. The proposal is an attempt to control the combustion process to occur near or as close as possible to TDC which will improve engine's performance. This is to be achieved by a control of the multipoint combustion using multipoint spark in the combustion chamber and in co-ordination with control of engine speed (piston speed) to avoid knock; it is hoped that the use of a higher compression ratio may be possible. The multipoint ignition system is to be arranged between the cylinder head and the piston to cover most of the combustion chamber. The research concerned the influence of spark plugs number and location on the engine performance and emissions. CFD is also exploited to deal with some specific problems like turbulent flame speed model, flame-wall interactions and viscous model. The project also will present a modeling of the combustion process in this engine, which was performed with CFD code.

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1. INTRODUCTION

Engine performance is influenced mainly by the ignition process. Traditionally, only a single spark is used to initiate the ignition system when air-fuel mixture reaches a pre-specified limit. It is important to have homogeneous distribution of air-fuel mixture inside every engine, which is nearly impossible mainly because of temperature difference. Thus complete combustion cannot be achieved which adversely influence the environment. Having efficient and reliable ignition system is essential because it not only starts the combustions but it is important to improve and sustain combustion stability. Lean burn system is one advanced approach that can enhance thermal efficiency while reducing emissions of the exhaust gas [1].

Recently, non-conventional ignition techniques such as multiple spark ignition methods have become more and more field of research in order to replace the conventional spark ignition systems. For this purpose, many researches concerning various ignition systems have been proposed; these include multipoint ignition by flame dispersion, plasma jet igniters, laser-induced cavity ignition, laser-induced multi-point ignition, flame jet igniters, pulsed-jet combustion, exhaust gas recirculation ignition systems [2-6], and various electrical and mechanical multipoint spark ignition systems; such as high-energy spark plugs, plug with a double spark, twin spark plug, series multipoint spark ignition system, multipoint ignition with a central electrode, multi-gap spark ignition system, and multi-plug ignition system. In addition, many researchers have investigated the numerical simulation of combustion process with multipoint ignition system using CFD software [7-12]. The multiple ignition system using non-laser devices also have been proposed by many researchers. A multipoint ignition engine includes a central electrode pair. A series multipoint ignition system has been developed by Minami K. [4]. Cupiał et al. [6] has examined a multipoint ignition system with multi-plugs operating on lean mixture using numerical and experimental approaches.

The material reviewed of multiple spark ignition system in engine testing has shown a significant reduction of NO_x emissions, increased combustion stability, and improved performance. Many researchers have used simulation software to investigate their models to avoid expensive costs for prototype building. One the powerful tool to the analysis and design of fluid and combustion inside the engine is a computational fluid dynamics (CFD). It is shown that (CFD) is a very useful tool for advancing in the development and optimization of these technologies. The interest of (CFD) for assisting in the understanding of the combustion process behavior in the engine is also important.

The proposed approach replaces the single spark with multiple ones, and then it strives to achieve faster and more stable performance. The proposed multipoint spark ignition system aims to allow the initiation of ignition at different air-fuel mixture levels which improves ignition duration and capability. The Compared to traditional ignition system which results in incomplete combustion, causing fuel wastage, reduced power and undesirable emissions, multi-spark ignition system results in better spark quality causing nearly complete combustion. When combustion is nearly completed, less emission, better energy conversion and more engine power could be achieved. In addition, engine noise is reduced because of the smoother engine run. Most engines need to have constant volume burn in order to operate efficiently. Thus, it is better to use multiple-sparks to ignite the charge at many locations. This also enhances the spark durability and increases combustion efficiency. Using multi-spark ignition system, the air-fuel mixture can be burned quickly since the flame propagates from the engine periphery to the center. This reduction in combustion time retards ignition timing which is conventionally before top dead center, can be retarded, whereby the loss can be suppressed that is generated when the rising piston is moving down by the high pressure in combustion chamber [13]. As a result, the use of multi-spark ignition system greatly enhances both engine output and efficiency. In addition, emphasis is given to proposal work to explore the feasibility of this interesting technology for practical applications concerning internal combustion engines.

2. FLUENT SOLVER

There are two solvers types used in the Fluent program which are pressure based and density based type. The pressure-based solver is one of the powerful solvers employs an algorithm which belongs to the projection method. This model solves the nonlinear momentum and continuity equations to satisfy the conservation of mass and the conservation of momentum laws [14]. To achieve the optimum solution for these equations iteration should be included. To gain the maximum accuracy, this process will be repeated until the convergence is obtained. In this research the pressure-based Navier-Stokes coupled algorithm which describes the fluid motion has been used [14].

3. TURBULENCE MODEL

The turbulent characteristic is used to improve and accelerate the combustion process inside the engine. The Fluent software used many turbulence models to solve the turbulent flow issues. These include Spalart-Allmaras model, Transition SST model, Reynolds stress model, k-omeg model, and k-epsilon model [14]. The ***κ-ε*** model is the most common model used in CFD codes to simulate the flow with turbulent conditions. This model is applied for fully turbulent flow. It based on two transport equations which are the turbulent kinetic energy (k) equation and the turbulent dissipation (***ε***) equation. The turbulent length scale is estimated from two properties of the turbulence field, usually the turbulent kinetic energy and its dissipation rate. The dissipation rate of the turbulent kinetic energy is provided from the solution of its transport equation. The ***κ-ε*** model was proposed by Launder and Spalding [15]. It has many applications in engineering and industry. In this simulation, the standard ***κ-ε*** model has been used because of his several advantages over other models: economy, strength, and accuracy [14].

4. DYNAMIC MESH MODEL

Since the piston in the SI engine moves between the top dead center and the bottom dead center, the mesh used to simulate the inside engine should be a dynamic mesh. Three methods are available in the Fluent to simulate the mesh motion inside the cylinder: smoothing methods, dynamic layering, and remeshing method [14]. In this simulation a prismatic mesh zones with a dynamic layering method has been used to describe the motion of the mesh boundaries. The dynamic mesh presented in this simulation is made up of top wall, cylinder, piston, and the fluid as shown in Fig. 3.

5. BOUNDARY CONDITIONS

This simulation considers a 2D axisymmetric geometry of the IC engine cylinder configuration. Simulation starts at IVC and ends at EVO, hence there are no valves involved. One of the most common boundaries encountered in fluid flow problems is the wall. Wall boundary conditions are used to bound fluid and solid regions. In viscous flows, the no-slip boundary condition is enforced at walls by default. For translational or rotational motion of the wall boundary, it is recommended to specify a tangential velocity component of shear. The shear stress and heat transfer between the fluid and wall are computed based on the flow details in the local flow field. The boundary conditions for current simulation are illustrated in the Table 1.

Table 1. The boundary conditions of the dynamic mesh

Wall motion conditions	Stationary wall
Shear conditions	No slip
Wall roughness height	0 [mm] constant
Wall roughness constant	0.5
Heat flux	0 [w/m^2] adiabatic
Heat generation rate	0 [w/m^3]
Wall thickness	0 [mm]
Inlet pressure	101325 [Pa]
Inlet temperature	298 [K]
Turbulent kinetic energy	1 [m^2/s^3]

6. COMBUSTION MODEL

Internal combustion engines require ignition of the air/fuel mixture to start the combustion process. The gasoline engine is ignited by a spark initiation and diesel engine by the compression of the mixture to the self-ignition point. ANSYS FLUENT has a built in spark model which is compatible with all combustion models in FLUENT: premixed, partially premixed, and auto-ignition [14]. In this paper a spark plug premixed combustion has been used. The simulation has been done using the commercial CFD Fluent software. Combustion process modeling was realized for two configurations of spark plug number and location: one central spark plug (Fig. 1) and two spark plugs (Fig. 2). Geometric mesh which described the shape of combustion chamber was made in the Cartesian co-ordinate system (Fig. 3). The numerical simulations began at 210ºCA and finished at 490ºCA. This meets the test engine valve timing (the intake valves closure and the start of exhaust valves opening).

During the modeling attention was focused on pressure and flame speed in the cylinder during the combustion process. For spark-ignited (SI)

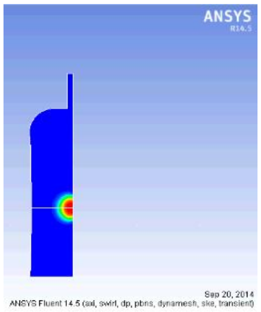


Fig. 1. Flame initiation for single spark plug

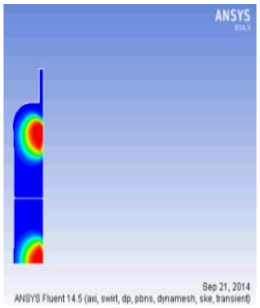


Fig. 2. Flame initiation for double spark plugs

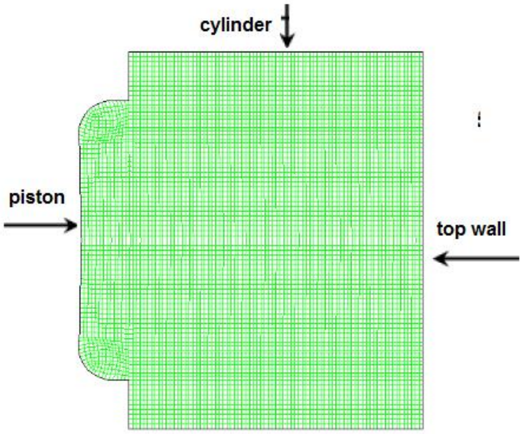


Fig. 3. Dynamic mesh geometry

engines fuel and air are mixed before entering into the combustion chamber. At the spark event, the mixture can be assumed to be homogeneous and the combustion process to be premixed. The investigated engine model is a spark ignition engine with premixed combustion model and pressure-based Navier-Stokes solution algorithm. The mesh is modeled as axisymmetric swirl two dimensional dynamic mesh contains fluid, piston and stationary cylinder head with time dependent solution. Axisymmetric swirl specifies that the swirl component (circumferential component) of velocity is to be included in your axisymmetric model. The standard k-epsilon (2-equations) viscous model has been used.

The Zimont flame speed model with constant turbulent flame speed is assigned for the simulation because it operates similar to the spark model used with the C-Equation combustion model (see the next paragraph). The geometry of the spark may be time dependent or fixed.

7. C-EQUATION OF PREMIXED COMBUSTION MODEL

The transport equation for the mean reaction progress variable *c* is given by Equation (1) [14]

$$\frac{\partial \rho c}{\partial t} + \nabla \cdot (\rho \overline{v} c) = \nabla \cdot (D_t \nabla c) + \rho_u U_t \mid \nabla c \mid \tag{1}$$

Where

D_t - turbulent diffusivity,
ρ_u - density of the unburned mixture
U_t - turbulent flame speed

The C-Equation diffusivity is modified such that [14]

$$\frac{\partial \rho c}{\partial t} + \nabla \cdot (\rho \overline{v} c) = \nabla \cdot ((\kappa + D_{tt}) \nabla c) + \rho_u U_t \mid \nabla c \mid \tag{2}$$

Where κ is the laminar thermal diffusivity

The effective diffusivity D_{tt} is given by [14]

$$D_{tt} = \begin{cases} D_t\left(1 - \exp\left(\frac{-t_{td}}{\tau'}\right)\right) & \text{if } t_{td} \geq 0 \\ D_t & \text{if } t_{td} < 0 \end{cases} \tag{3}$$

Where is $t_{td} = t - t_{id}$ and t_{id} denotes the time at which the spark is initiated. Additionally, τ` is an effective diffusion time [14].

The analysis were carried out for centered single spark and double sparks with equal distance from the combustion chamber's symmetric axis. In both cases the spark has fixed size with initial radius 2 [mm] and energy 0.1 [J].

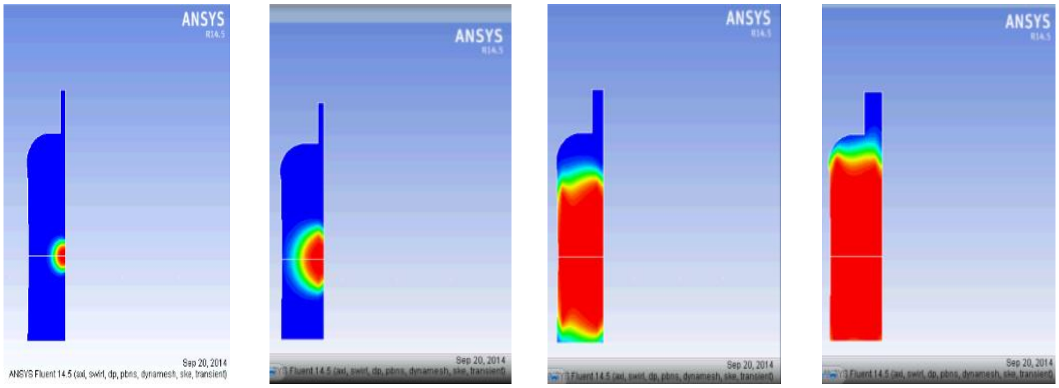
8. RESULTS AND DISCUSSION

At the end of the simulation, the TIFF files for the contours of progress variable at different crank angles are obtained. Some examples of the combustion process sequences for single spark plug are presented in Fig. 4 (a-d). Other examples for combustion process sequences for double spark plugs are shown in Fig. 5 (a-d).

Modelling results are analysed using fluent postprocessor. Pressure in function of time steps curves were made. The results of pressure and flame propagation modelling for both cases were compared. These values are actual and averaged for all the combustion chamber volume values.

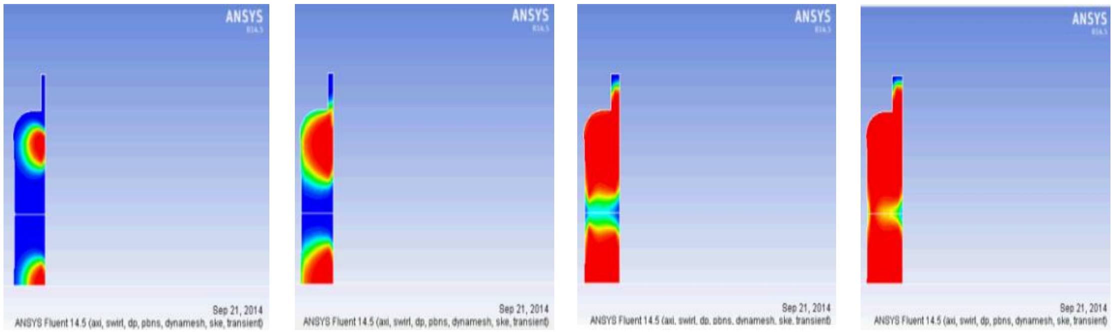
The results from the simulation show significantly faster flame propagation in case of two spark plugs as seen in Figs. (6–9). The same results can be obtained from Figs. 10 and 11. The time for initiation of ignition is reduced using double sparks compared to a single spark resulting in shorter combustion duration; which is defined as the time between the start of the ignition and 100% fuel burning [16]. In addition, the distance which the flame has to travel to ignite the fresh charge decreases resulting in flame acceleration, less heat losses, and higher engine's efficiency. Moreover, the turbulence motion inside the cylinder caused by the combustion chamber shape and the interaction between the flame waves enhances the diffusion process and consequently increases efficiency of the combustion process [1]. Morsy [1] in his paper has reported that the multipoint ignition induced by laser ignition is an advance technique to avoid problems associated with lean mixture ignition such as misfire, pressure pulsation, and early flame quenching [17,18].

In the two spark plugs configuration, the modelled pressure is higher (Fig. 13) and its maximum (5.5 MPa) occurs earlier than in one spark plug configuration where $p_{\max}$ = 2.9 MPa (Fig. 12). Moreover, these figures shows that combustion duration for a single plug is very long comprised with double spark plugs resulting in lower engine emissions and higher performance [6].



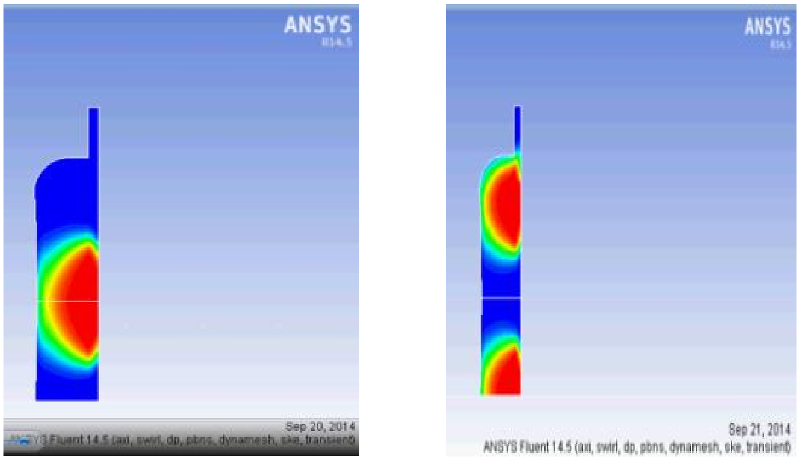
(a) (b) (c) (d)

Fig. 4. (a)-(d) Ignition process (single plug ignition)



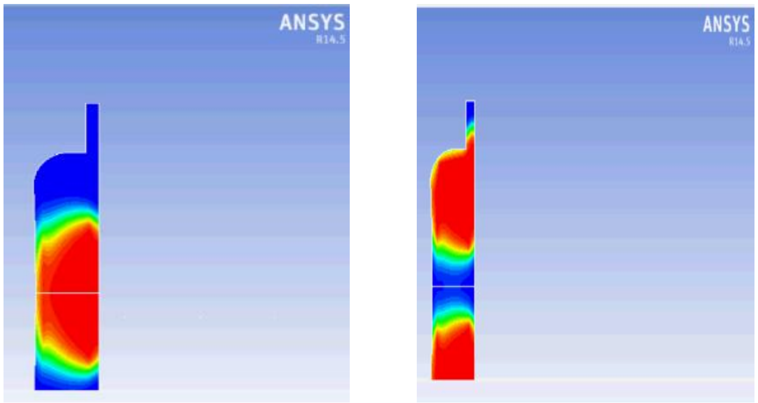
(a) (b) (c) (d)

Fig. 5. (a)-(d) Ignition process (single plug ignition)



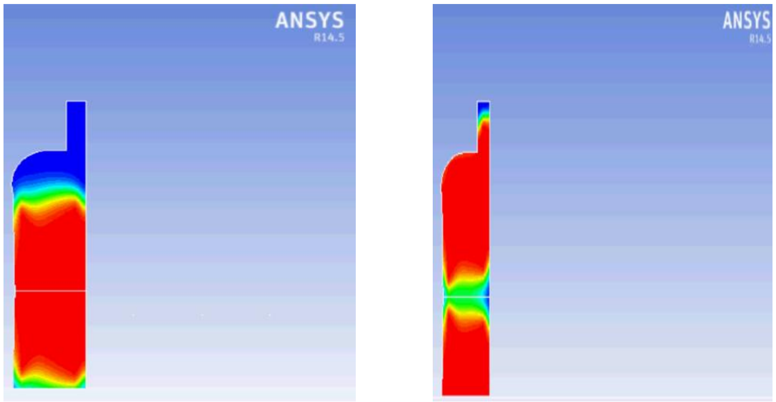
(a) **(b)**

Fig. 6. Flame propagation for single plug ignition (a) and double plugs ignition (b) at crank angle 730º



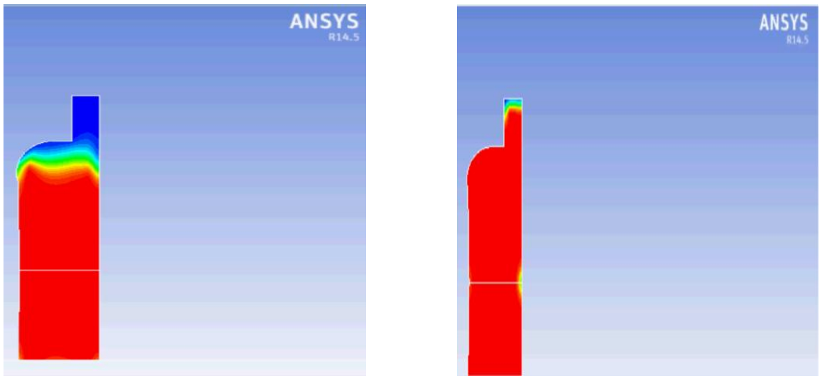
(a) **(b)**

Fig. 7. Flame propagation for single plug ignition (a) and double plugs ignition (b) at crank angle 734º



(a) **(b)**

Fig. 8. Flame propagation for single plug ignition (a) and double plugs ignition (b) at crank angle 739º



(a) **(b)**

Fig. 9. Flame propagation for single plug ignition (a) and double plugs ignition (b) at crank angle 745º

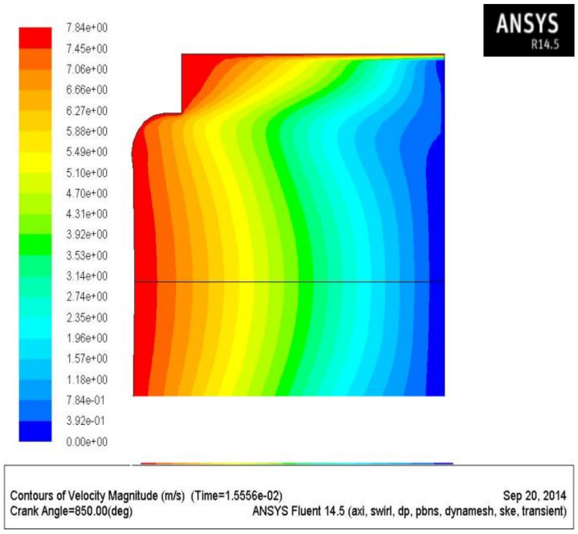


Fig. 10. Velocity magnitudes for single spark ignition

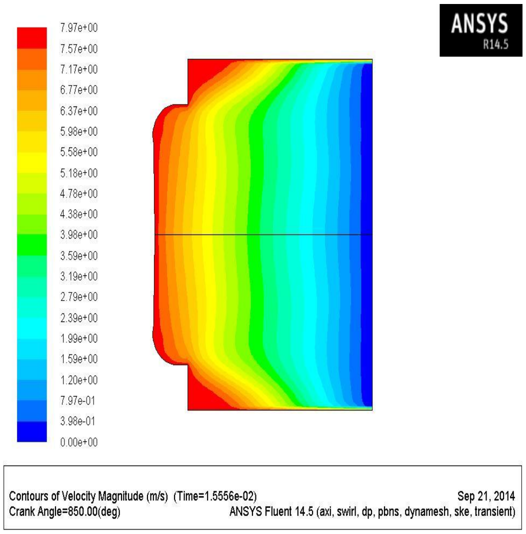


Fig. 11. Velocity magnitude for double spark ignition

The NO_x concentration in the exhaust gases of a spark ignition engine is affected by oxygen concentration and combustion temperature. This as a very serious problem for very lean mixtures, because the speed of the flame propagation decreases to low values resulting in decreasing engine's efficiency. Therefore, to overcome these problems in the engines and to increase their lean operation performance they are equipped with two or more spark plugs in different locations to shorten the distance which the flame should overcome to complete the combustion process [1].

In addition, a turbulence model has been used in the simulation to accelerate mixing process, increase flame speed and to compensate the loss in combustion duration. The higher combustion temperature and pressure inside the engine caused by lower engine heat losses because of shorter burning time leading to higher thermal efficiency and engine power output [19,20]. It has been reported that multipoint ignition is a good solution to avoid problems such as early flame quenching, partial burn, misfire, and pressure pulsation associated with lean mixtures burning [17,18].

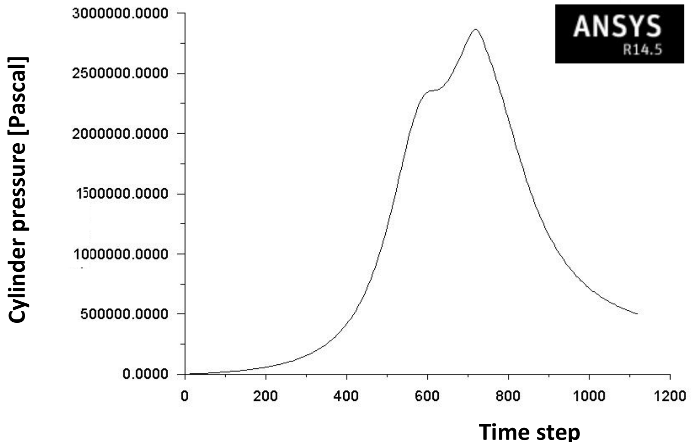


Fig. 12. Pressure in cylinder for single spark plug

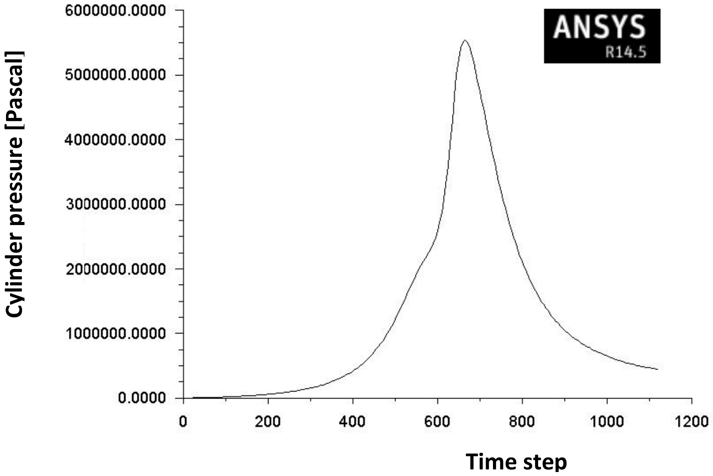


Fig. 13. Pressure in cylinder for double spark plugs

9. CONCLUSION

Recent SI engine research which is powered by premixed mixture using CFD Fluent shows that when number of active spark plugs increases non-repeatability rate decreases while indicated pressure and efficiency increases. Also, it reduces duration of combustion. Numerical modelling of the combustion process for gasoline engine with spark plug ignition has presented an improvement in engine performance with multi-spark plugs in a cylinder. It increases flame propagation velocity particularly during lean mixture combustion which causes a decrease in flame speed and deterioration of engine parameters [7].

The two spark plugs configuration used in the simulation compared to the single spark model shows higher pressures in the cylinder and a faster increase of those pressures [7]. The maximum pressure angle amounts to 730 time step (central spark plug) in Fluent and 680 time step (two spark plugs) in Fluent.

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COMPETING INTERESTS

Author has declared that no competing interests exist.

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