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Analytical Study of Flame Front Geometry for Gasoline Powered Engine

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Abstract: **Flame front surface area is theoretically analyzed for a spark-ignition engine, having hemispherical shaped combustion chamber and flat head spark ignition engine with two spark plugs located axis symmetrically on cylinder head, between cylinder axis and cylinder wall. A computer code is developed based on purely geometric consideration of the flame development process in combustion chamber on geometric features of the flame front. A hemispherical combustion chamber, also known as the HEMI, has a combustion chamber in the shape of a half sphere. The hemispherical combustion chamber has an advantage of cross flow design that allows the engine to breathe better. This is to give some turbulence to the engine. The hemispherical combustion chamber generates more power as the air does not have to turn at right angles and the resistance to its motion is less. The key advantage of a hemispherical combustion chamber is that its surface area to volume ratio is the least in the category as compared to other designs like flat head, wedge heads, etc. and therefore they have a superior thermal efficiency than other engines. Also, as the valves are located cross-wise, the valves can be made large resulting in better breathing of the engine The effects of the stroke/bore (S/B) ratio on the performance parameters of hemispherical head engine having dual-spark ignition (DSI) were investigated theoretically by using a two zone thermodynamic cycle model. The engine performance parameters, i.e., engine power, indicated mean effective pressure, specific fuel consumption, and thermal efficiency, were computed for various conditions. The obtained results for DSI operation have been compared to those of a single-spark-ignition (SSI) condition for both hemispherical cylinder head spark ignition engine and flat head spark ignition engine.**

Keywords: **spark ignition engine, single-spark-ignition, dual-spark ignition.**

1. INTRODUCTION

When the spark plug is mounted at the center of the cylinder head, the distance travelled by the flame front to the most distant part is the shortest. The central position of the spark also ensures the maximum flame front surface area. As a result, the rate of heat evolution and the rate of pressure rise are higher than those with a side mounted spark plug. The two spark plugs suitably located reduce the flame travel paths and give a higher rate of pressure rise. The thermal efficiency is increased and the specific fuel consumption is decreased. With large diameter cylinders the use of two plugs give better performance results, whereas in small cylinders a single plug will give satisfactory results, owing to reduced travel path. Although, there have been numerous studies performed on the optimum spark-ignition (SI) engine combustion chamber design, considerable differences in production engines are sufficient evidences that this question is still unresolved, after decades of development [9]. Although there are many options for combustion chamber shape, number and location of spark plug(s), size and number of the intake and exhaust valves, and intake and exhaust port design, there is no single solution to this complex multi goal problem. But during the past few decades a consensus has developed on SI engine combustion chamber design, satisfying „faster-burning criteria. A chamber design in which the fuel-burning process takes place faster, that it occupies a shorter crank angle interval at a given engine speed [9], results in direct efficiency gain due to the approach to the theoretical Otto-cycle. Furthermore, faster-burning in engines produces a more robust and repeatable combustion pattern that permits operation with substantially large amount of exhaust gas recirculation (EGR), or with very lean mixtures, without impairing engine operation stability [10].

Thus, short combustion duration (faster- burning) in combination with heavy EGR (or very lean mixtures) has a potential to achieve greater emission control in combustion chamber along with some improvement in fuel economy due to the reduced pumping work, reduced gas temperature and reduced heat losses [1,2]. Faster burning also increases resistance to knock that can allow the fuel economy advantages associated with higher compression ratios to be realized [5].

A number of different combustion chamber design techniques for accomplishing faster burning can be categorized into two groups: [5,11].

Affecting the fluid motions in the chamber to increase burning rate via increasing Turbulence level altering the combustion chamber geometry to increase burning rate via decreasing the flame propagation distance and increasing the frontal area of the flame.

The first one involves the generation of more turbulent charge motion via the use of intake flow restrictions or combustion chambers with large swirl or squish regions. Increased turbulence results in higher transport rates within the flame and in the increased distortion of flame front, both of which increase the burning rate. However, intake restrictions increase the pumping work required to induct the charge, and more vigorous in-cylinder gas motion results in added heat loss to the combustion chamber walls. The second Approach to achieve faster-burning aims at increasing the frontal area of the flame and at decreasing flame propagation distance as the flame propagates into the unburned charge. This method requires optimization of the chamber shape and the location of the spark plug and/or the adoption of multipoint ignition [1].

The stroke/bore (S/B) ratio is one of the most important geometric parameters for modern spark-ignition (SI) engines because, it determines the overall dimensions of the engine for a given displacement [12,13]. However, there are only a few studies performed to investigate S/B ratio effects on engine performance and exhaust emissions for two- and four-stroke engines. In general, a longer stroke leads to higher thermal efficiency through faster burning (reduction in combustion duration) and lowering the overall chamber heat loss [13]. A shorter stroke decreases engine friction, most noticeably at higher engine speed [14]. It also increases the maximum operating speed, maximum power, indicated mean effective pressure (imep), and also blow-by of the engine [6]. In addition, the larger bore will provide more area for poppet valves in four- stroke engines [13]. Hence, increasing the number of valves per cylinder for a given cylinder bore improves engine breathing. In this study, using the second approach mentioned above, the effect of variation of spark plug locations on geometric features of the flame front is investigated for an SI engine having hemispherical-shaped combustion chamber with single and two spark plugs on cylinder head. The use of multiple spark plugs is suggested by [23] to improve the engine performance in a variable stroke engine. It has been clearly understood in the literature review that investigations on the stroke to bore (S/B) ratio are limited. The centrally located single plug is suggested to have an optimal configuration, but it cannot be applied commonly because of some designing limitations because of this ,it is considered to use multiple spark-plug configurations as a suitable solution[24]. For these reasons, this study is devoted to investigate the effect of the S/B ratio on the performance parameters for dual-spark-ignition (DSI) engine and SSI engine conditions. The results of the identical plug were compared to those of single-plug configuration. Such comparisons showed that dual spark plug (hemispherical head) generally gives slightly higher engine performance parameters than the single plug (hemispherical head) and single plug (flat head) for selected S/B ratios. On the other hand, increasing the S/B ratio improves the engine performance in a decreasing manner.

2. LITERATURE REVIEW

The history of using multipoint ignition, especially twin-spark plugs per cylinder, was longer than three decades. Most of the studies available in the literature are experimental [1, 2, 3]. Quader [3], used a specially modified combustion chamber installed between the head and cylinder block. Spark plugs were mounted to the side access ports of this chamber. He found that fast burn was achieved by dual-spark plug ignition, and lean limits of stable operation were extended to leaner mixtures with dual-spark plugs. Kuroda et al. [1] experimentally optimized combustion chamber shape and spark plug locations to equalize the flame propagation from two spark plugs. They showed that fast burn overcomes the slow burn limitation of conventional engines and greatly extends the stable combustion range under heavy exhaust gas recirculation(EGR) conditions, with resulting marked reduction in NOx emission, and improved fuel economy. Hillyer and Wade [4], and Scussel et al. [5] carried out an experimental test program on the Ford PROCO stratified charge engine having a combustion bowl in piston, and dual- ignition system. They found that dual ignition system produces reliable, misfire-free operation with the dilute mixtures and high

EGR rates which result in NOx control capability coupled with limited HC and CO control. Witze [6] performed an experimental study to investigate the trade-off that exists between spark locations and swirl rate. The goal of his study was optimization for the fastest burn.

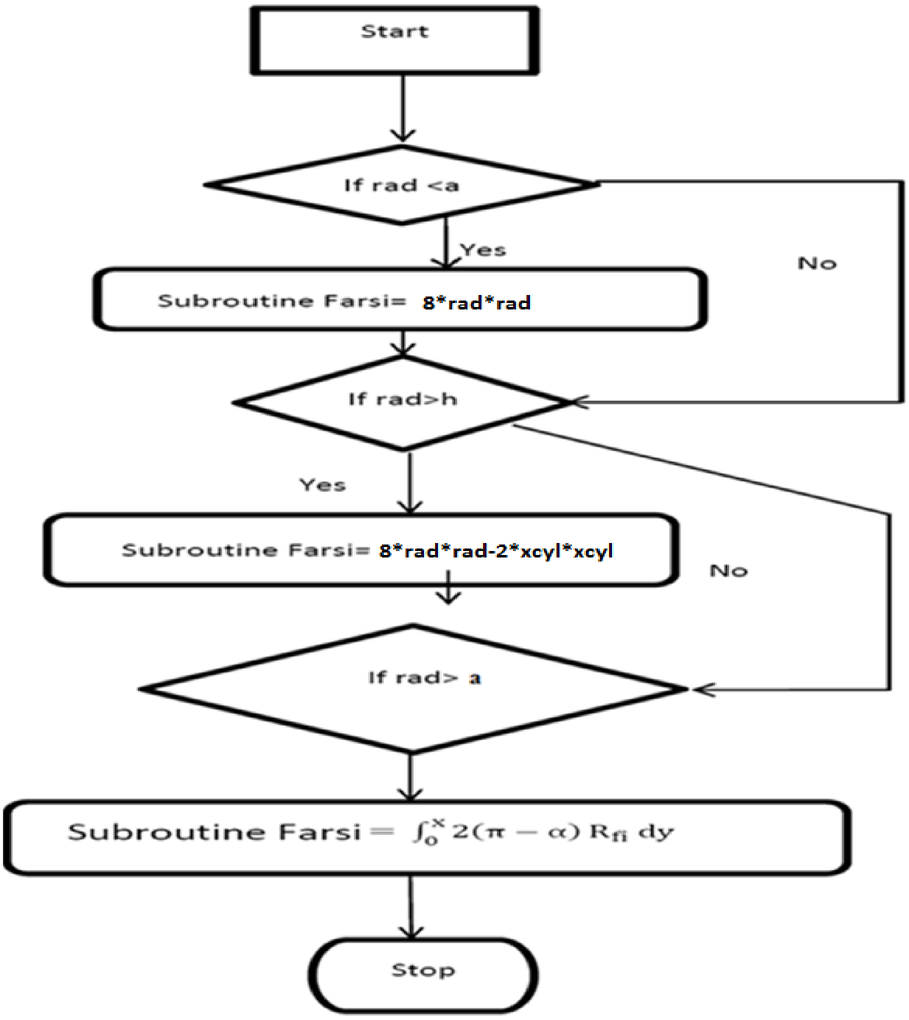
There are limited number of theoretical simulation studies on using twin-spark plugs in SI engines [7,8], and only a few of them are based on a quasi-dimensional thermodynamics combustion models [7]. Bozza et al. [7] carried out both experimental and theoretical analysis on a twin spark S.I engine equipped with a variable valve timing device. Their aim was to investigate proper combination of variable valve timing device position and spark advance for different engine operating conditions. Therefore they didn"t change the location of spark plug in their study. Although, there are some engines production having dual ignition chamber (DIC), i.e. two spark plugs on combustion chamber, there has been a scarcity in the existing literature on the investigation of the effects of using two sparks plug and variations of plug locations by geometric consideration of the flame development process and, on thermodynamic modeling studies of combustion process for SI engines having DIC.

3. MODIFICATION IN THE PROGRAM

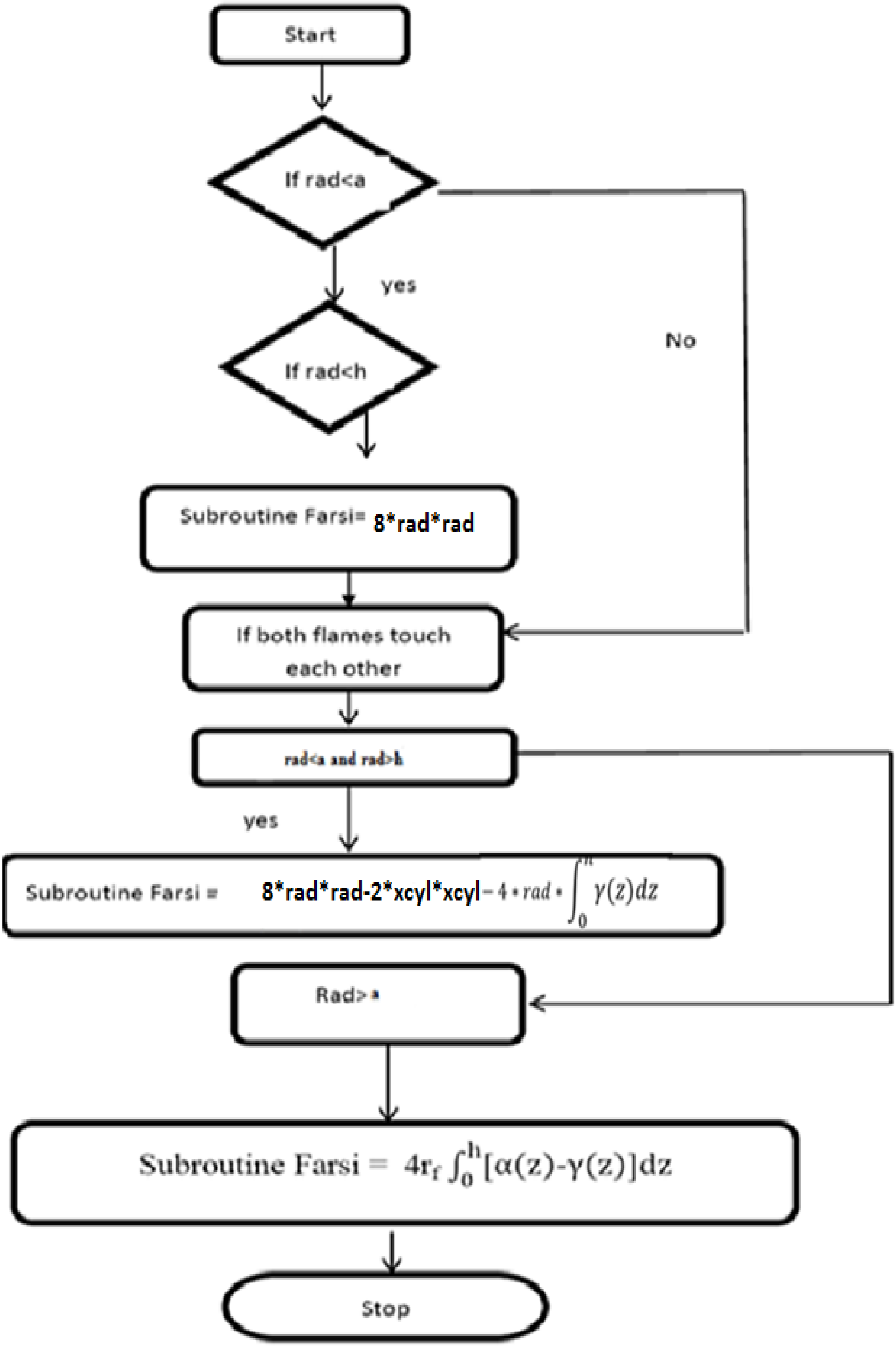
Some modification was made in the computer program originally developed by Benson and H.N Gupta, for calculating the performance parameter of single and dual spark plug ignition engine for flat disc head type combustion chamber.

Since burned mass fraction rate depends upon flame front area, and heat loss depend upon surface area of combustion chamber contacted by hot gases. hence by changing subroutine FARSI and subroutine CONAR in the original program a new model is developed for calculating the performance parameter of single and dual spark plug ignition engine for combustion chamber.

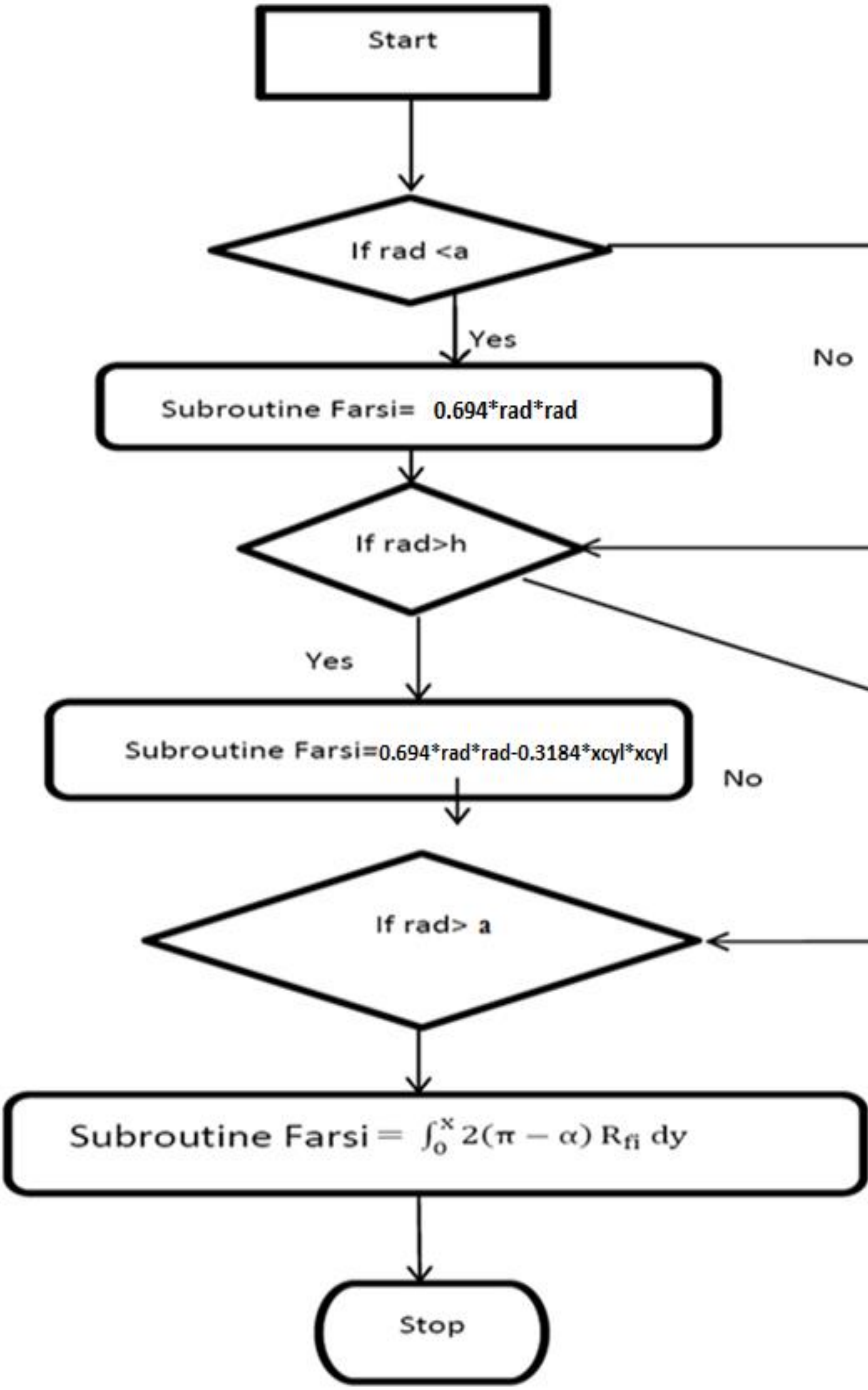
FLOW CHART FOR CALCULATING FLAME FRONT AREA FOR SINGLE SPARK (FLAT HEAD)



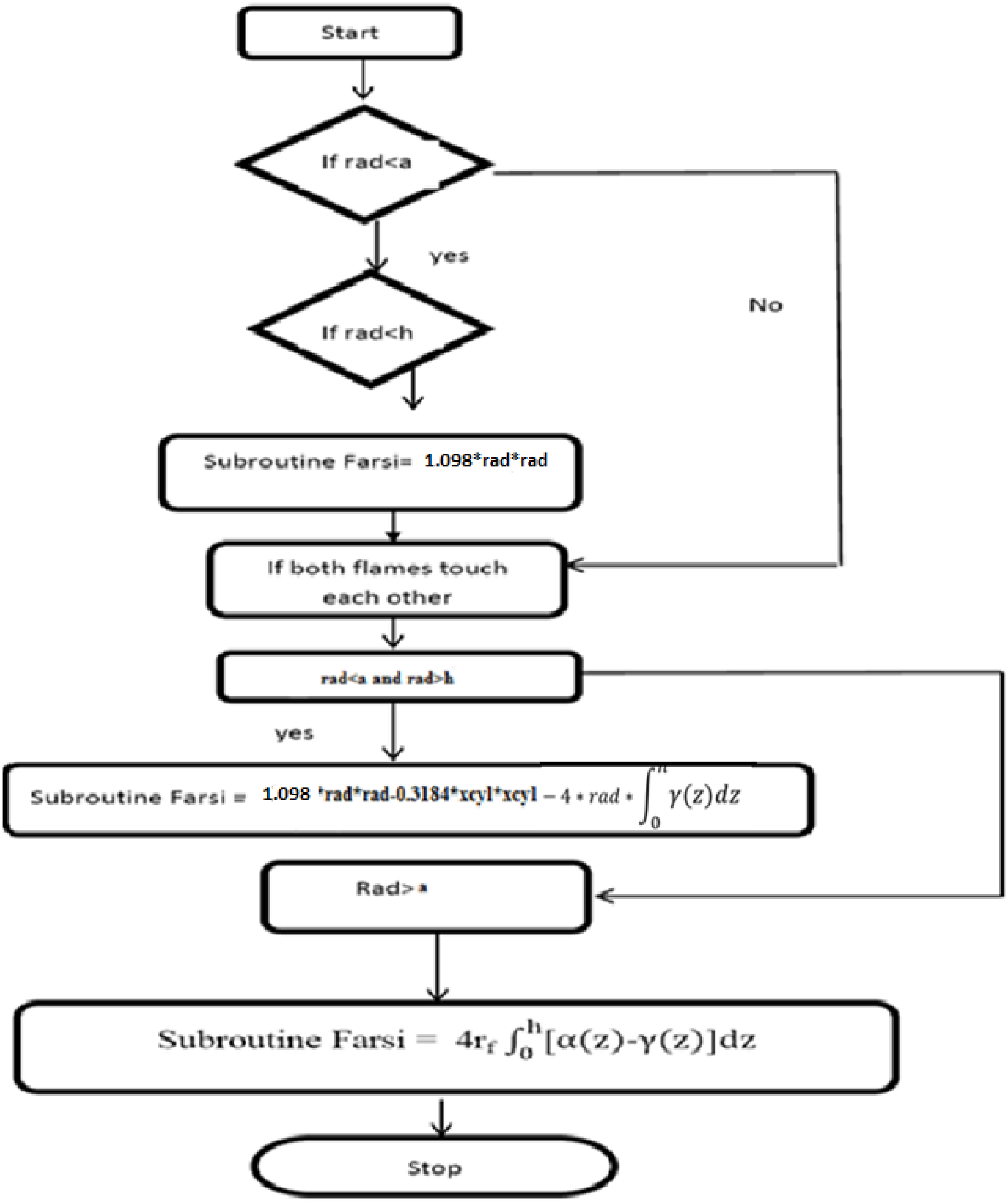
FLOW CHART FOR CALCULATING FLAME FRONT AREA FOR DUAL SPARK (FLAT HEAD)



FLOW CHART FOR CALCULATING FLAME FRONT AREA FOR SINGLE SPARK (HEMISPHERICAL HEAD)



FLOW CHART FOR CALCULATING FLAME FRONT AREA FOR DUAL SPARK (HEAMISPHERICAL HEAD)



4. PROCEDURE

A simulation program has been developed for the presented quasi-dimensional SI engine cycle model. Input parameters of the program are engine speed n, equivalence ratio Φ, cylinder diameter Dcyl, compression ratio, distance of ignition point from the cylinder axis r_S, spark-plug number, spark advance angle θs, stroke length, connecting rod length, properties of fuel, ambient pressure, and temperature. After determining the intake conditions, the thermodynamic state of the cylinder charge was predicted by solving the arranged first-order ordinary differential equations for each process by taking the crank angle increment as 1°. The STINT subroutine, which uses the Runge-Kutta methods, was used to integrate the governing equations. At the start of combustion [at θs before top dead center

(TDC)], the initial value of the burned gas temperature was determined as the adiabatic flame temperature. The initial value for the mass fraction burned was predicted from the cosine burn rate formula. Laminar burning was assumed during the ignition delay period. After the delay period was terminated, combustion was computed as a fully developed turbulent flame process. Throughout the simulation, the thermodynamic state of cylinder content was determined.

5. MODEL VALIDATION

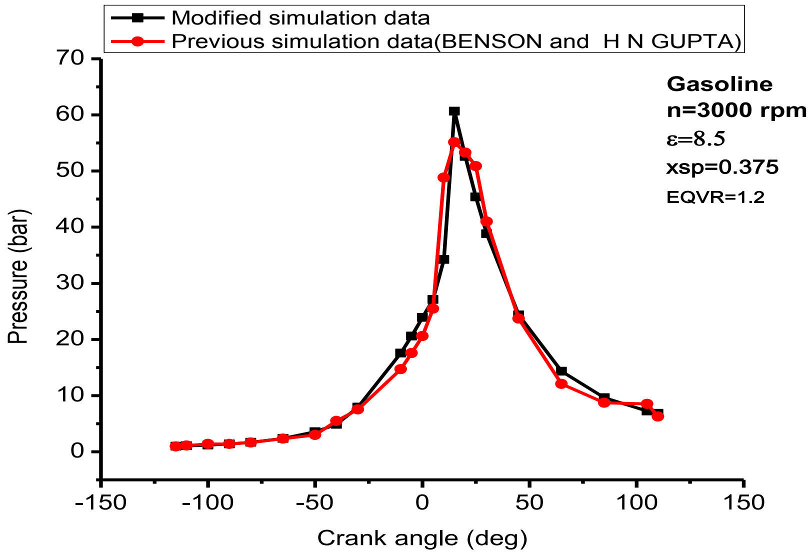


Figure 1. Comparison of predicted cylinder pressure values with previous simulation program for SIC

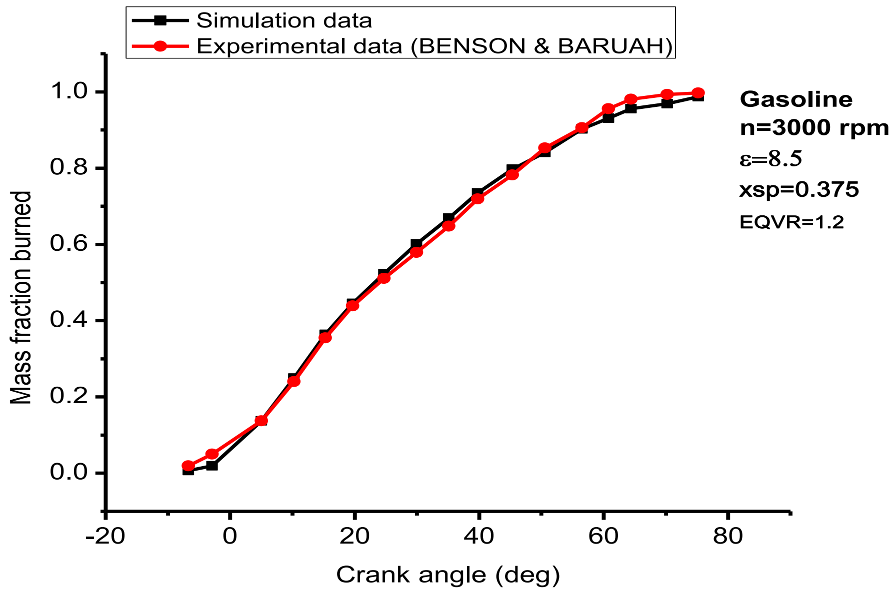


Figure 2. Comparison of predicted mass fraction burned values with experimental data for DIC

It is necessary to validate the predicted values with the available experimental data, before use of a simulation for a parametric investigation. In a quasi-dimensional engine cycle simulation, the comparisons of predicted values are made, generally, with pressure-crank angle data or burned mass fraction-crank angle data.

Figure 1 shows predicted and previous simulation work data for cylinder pressure values versus the crank angle. The predicted values of the mass fraction burned are compared to experimental value of Benson and Baruah in Figure 2 [25]. The predicted values are in excellent agreement with the previous data in figure 1; therefore, the presented model has an enough level of confidence for parametric investigation.

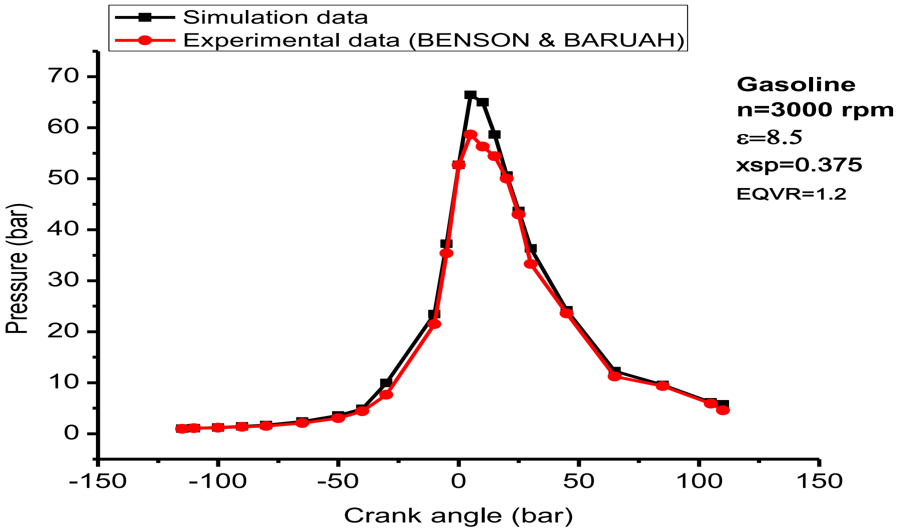


Figure 3. Comparison of predicted cylinder pressure variation versus cylinder data for DIC

It can also be seen in Figure 8 that for dual spark plug case predicted pressure values are in excellent agreement with the experimental values of Benson and Baruah [25].

6. RESULTS AND DISCUSSIONS

COMBUCTION DURATION AND CYLINDER DIAMETER (Dcyl):

Combustion duration is an important parameter in combustion, and its affects overall performance of engine. Figure 10 below shows that combustion duration decreases when diameter of cylinder is decreased from 100 to 70 and it shows similar behavior for single and dual spark plug hemispherical head engine and flat head engine respectively.

This is because as diameter of cylinder is increased flame will have to travel a greater distance in comparison with smaller diameter engines hence combustion duration will also increase. And combustion duration for dual is smaller than single for hemispherical head engine and flat head engine respectively because in dual spark plug flame front will have to travel shorter distance then single since flame front area increases in case of dual. As shown in the figure, dual-spark configuration for hemispherical head engine gives 13.12% lesser combustion duration than single-spark configuration (hemispherical head engine) at Dcyl=90 and. 2.9% lesser combustion duration than dual-spark configuration (flat head engine) at Dcyl=90 .

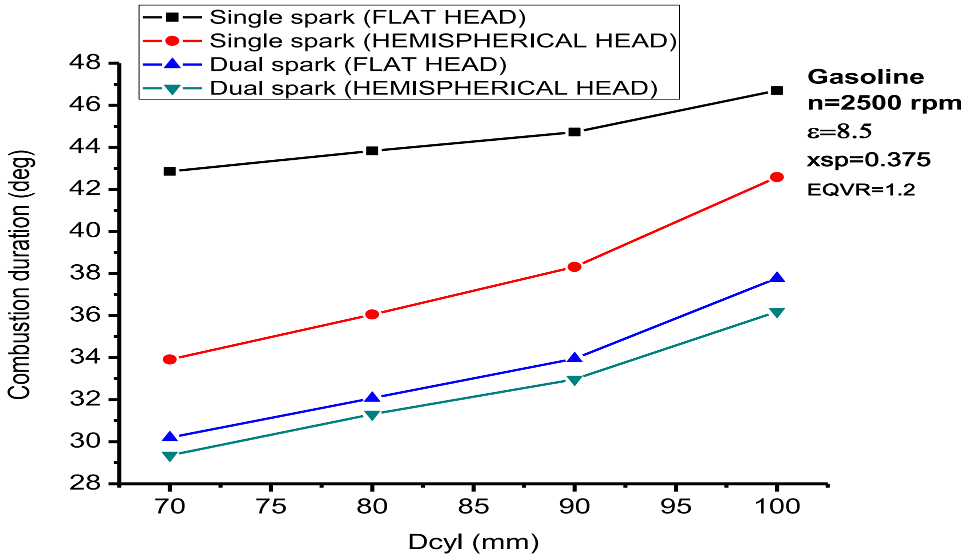


Figure.4 Combustion duration versus cylinder diameter (Dcyl)

PRESSURE VERSUS CRANK ANGLE:

It can be seen from Fig 5. the peak pressure for dual spark plug (hemispherical head) engine are higher than dual spark plug (flat head) engine because in dual spark plug (hemispherical head) have less combustion duration than dual spark (flat head)engine. Here the peak pressure for dual spark plug (hemispherical head) engine are 6% higher than dual spark plug (flat head) engine and 10.51% higher than single spark plug (hemispherical head) engine and 14.31% higher than single spark plug (flat head) engine.

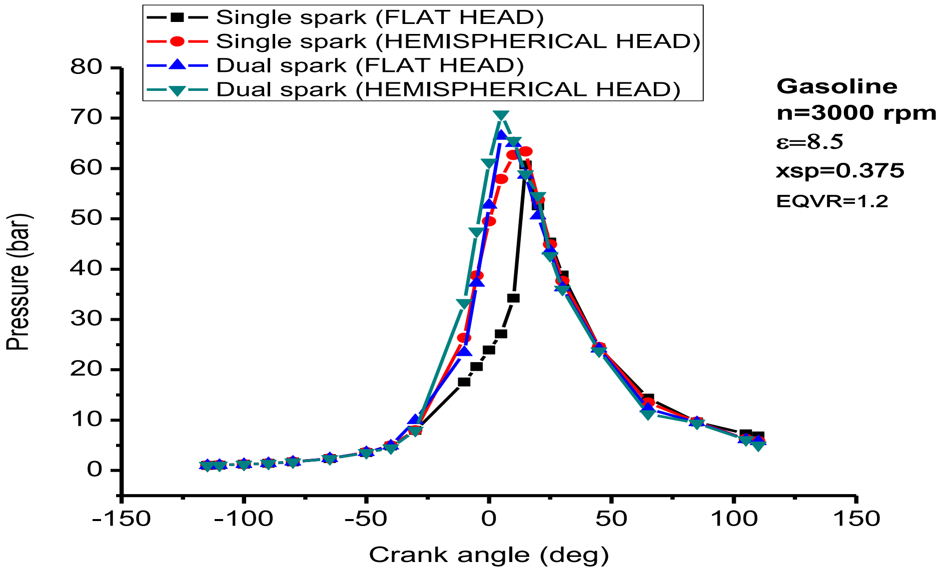


Figure.5 Pressure versus crank angle

INDICATED MEAN EFFECTIVE PRESSURE VERSUS SPARK PLUG LOCATION:

In this study, Mean indicated pressure, indicated specific fuel consumption were predicted for both single and dual spark configurations for both flat head and hemispherical head engine. The comparisons were carried out at five spark-plug locations. Because of the dimensionless distance of the spark plugs from cylinder center is defined as Rsd = rs/R, the examined spark-plug locations become Rsd = 0.0, 0.25, 0.50, 0.75, and 1.0. Here Rsd = 0.0 corresponds, inevitably,to a centered location of single-spark plug for both flat head and hemispherical head engine while all the other spark plug locations were examined for single- and twin-spark plugs for both flat head and hemispherical head engine. Equivalence ratio, and compression ratio were chosen as ϕ= 1.2 and ε = 8.5 .

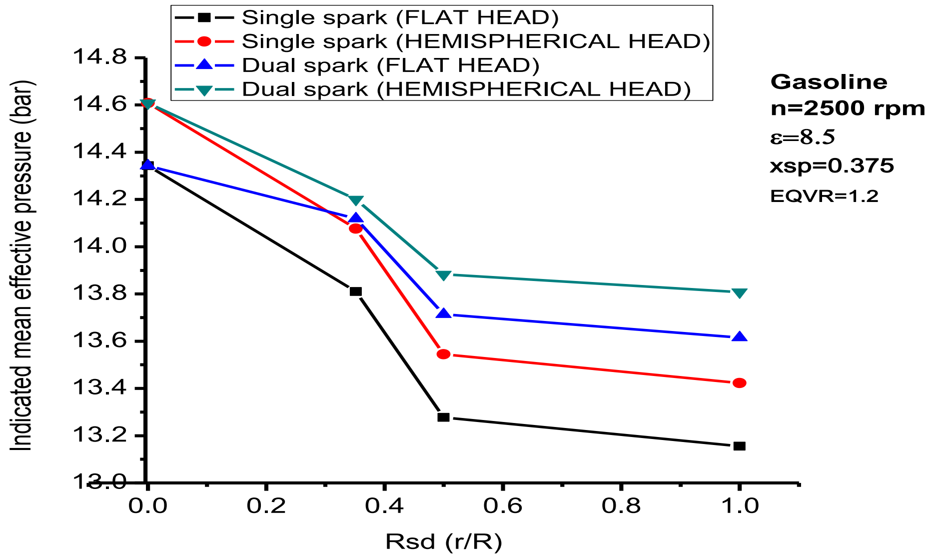


Figure .6 Indicated mean effective pressure versus spark plug position

The effects of spark location on indicated mean effective pressure are shown in Fig 6. , for single- and twin-spark configurations for both flat head and hemispherical head engine. The best results for indicated mean effective pressure were obtained for centrally located single-spark plug (hemispherical head) and moving the plug away from the central location results in decreases in indicated mean effective pressure values depend upon the plug location, for both single- and twin-spark engines. Although the variations are nearly linear with respect to plug location for both single and dual plug cases, the dependence of indicated mean effective pressure

on plug location is considerably stronger for single-plug case than twin-spark (hemispherical head) case, as given in Fig. As shown in the figure, even sidewall hemispherical head engine for twin-spark configuration (rsd = 1.0) gives closer indicated mean effective pressure value (14 bar) to hemispherical head engine for single-spark configuration (13.80 bar) that located at rsd = 0.375. These decreases in pressure values with increasing distance between cylinder center and spark location result from the increases in the combustion duration dependent on increase in flame traveling length with moving the plug location away from center to sidewall.

INDICATED SPECIFIC FUEL CONUMPTION VERSUS SPARK PLUG LOCATION (Rsd):

Variation of indicated specific fuel consumption with single and twin-spark configurations for both flat head and hemispherical head engine and different plug locations has been given in Fig 7. we know that increase in indicated mean effective pressure results in decrease in specific fuel consumption, and vice versa. This situation is shown in the figure 7. The minimum fuel consumptions have been obtained with centrally located single-spark plug for both flat head and hemispherical head engine arrangement. Twin-spark plugs located closer the center give second best fuel economy. Steeper increase in indicated specific fuel consumption with increasing radial distance of plug location from center for single-spark engine than twin-spark engine is also given in Fig 7.

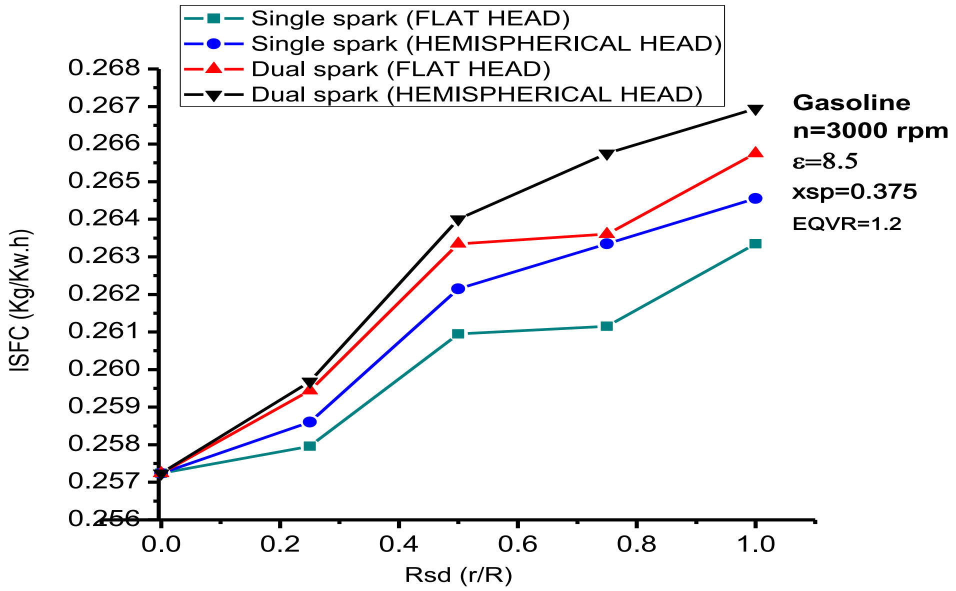


Figure.7 Variation of indicated specific fuel consumption versus spark plug location (Rsd)

7. CALCULATION OF PERFORMANCE PARAMETER

INDICATED THERMAL EFFICIENCY:

Figure 8 shows thermal efficiency variations versus cylinder diameter. It is directly related to heat loss and combustion durations. The dual-plug position(hemispherical head engine) gives slightly higher values than the single plug (hemispherical head) as well as the dual-plug position (flat head engine) for same spark plug position i.e. at xsp=0.375.. The cylinder diameter has an important effect on thermal efficiency, and it increases as the cylinder diameter decreases with a decreasing manner for all spark-plug configurations. These variations can be explained on the basis of the heat loss and combustion duration above. The decrease in heat loss leads to increases in imep, and thus, thermal efficiency increases. Further, a decrease of the combustion duration closes up the engine cycle to the ideal Otto cycle, which has the best thermal efficiency known.

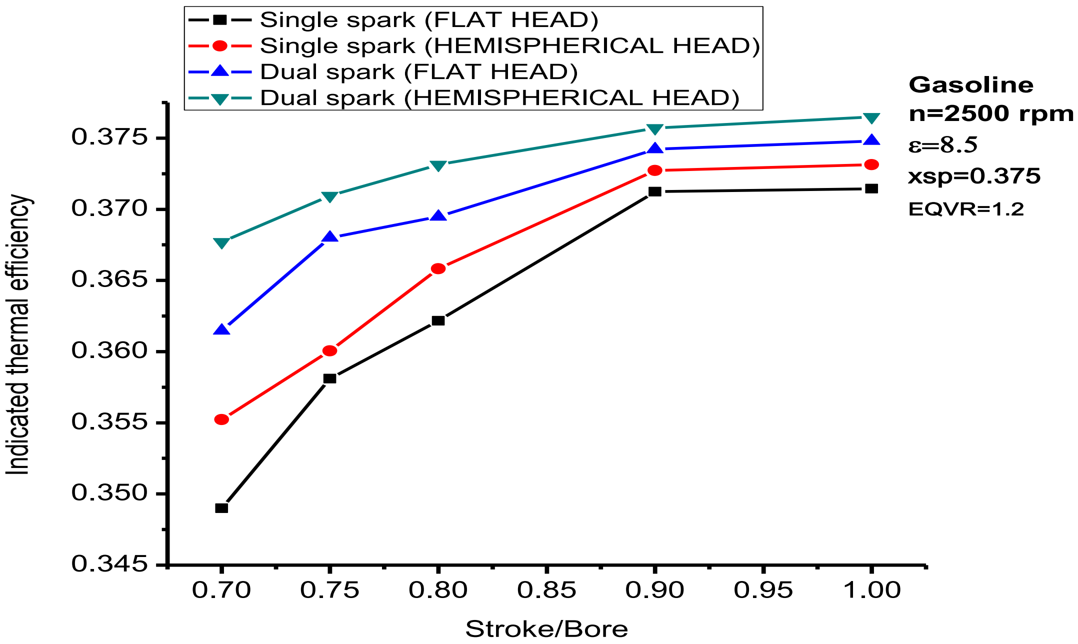


Figure.8 Indicated thermal efficiency versus stroke/bore ratio

INDICATED MEAN EFFECTIVE PRESSURE:

Indicated mean effective pressure (imep) is an important parameter because it is independent from the engine dimensions and used to improve correlations for engine operation, especially engine friction. The comparison of the indicated mean effective pressure versus cylinder diameter is shown in Figure 9 . As seen from the figure 15, the values of imep rise as the cylinder diameter decreases with a decreasing manner for all spark locations. Additionally, dual plug (hemispherical head engine) has slightly higher values than single plug (flat head engine) as well as dual-plug position (flat head engine) for same spark plug position. It is noted here that the use of dual-plug configuration (hemispherical head engine) has obviously an advantage as the cylinder diameter decreases compared to the single plug. According to figure 15, dual spark plug (hemispherical head engine) gives 2% greater value of indicated mean effective pressure than single plug (hemispherical head engine) and 4.3% single plug (flat head engine) at stroke/bore ratio=0.9.

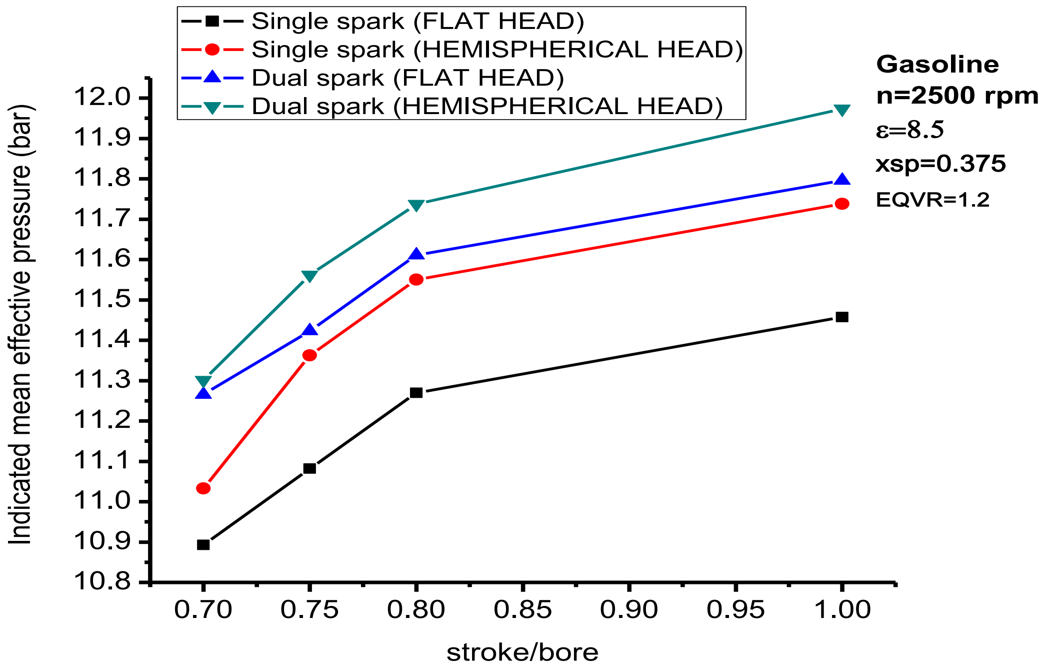


Figure.9 Indicated mean effective pressure versus stroke/bore ratio

BRAKE MEAN EFFECTIVE PRESSURE:

Brake mean effective pressure (bmep) is an important parameter because it is independent from the engine dimensions and used to improve correlations for engine operation, especially engine friction. The comparison of the Brake mean effective pressure versus cylinder diameter is shown in Figure . As seen from the figure 16, the values of imep rise as the cylinder diameter decreases with a decreasing manner for all spark locations. Additionally, dual plug (hemispherical head engine) has slightly higher values than single plug (flat head engine) as well as dual-plug position (flat head engine) for same spark plug position. It is noted here that the use of dual-plug configuration has obviously an advantage as the cylinder diameter decreases compared to the single plug.

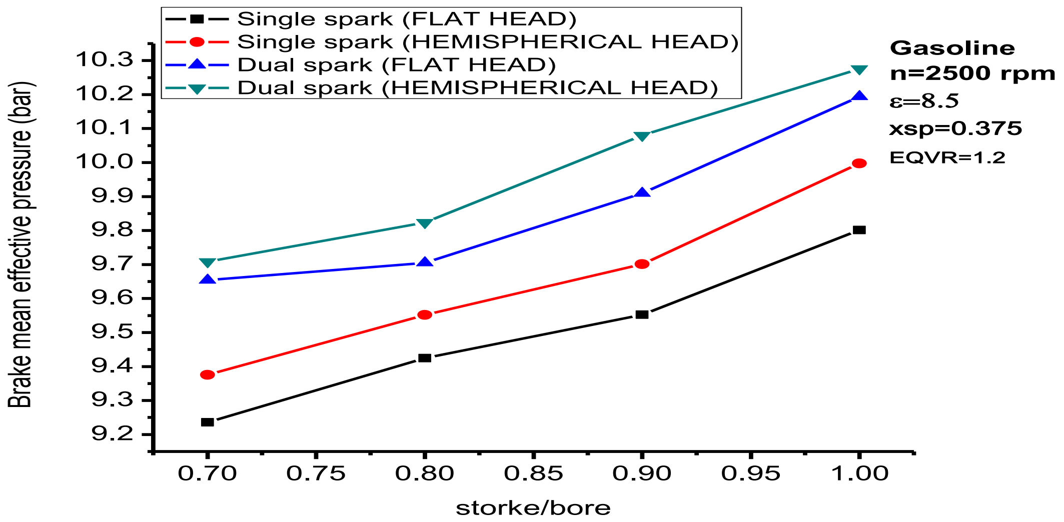


Figure10. Brake mean effective pressure versus stroke/bore ratio

INDICATED SPECIFIC FUEL CONSUMPTION:

Figure 11 shows indicated specific fuel consumptions (isfc) versus the cylinder diameter for spark-plug configurations. The values of isfc decrease as the cylinder diameter decreases for spark locations. Additionally, dual plug (hemispherical head engine) has slightly lower values than single plug (flat head engine) as well as dual-plug position (flat head engine) for same spark plug position. The variations in isfc are direct results of variations in thermal efficiency. As well known, indicated specific fuel consumptions vary inversely to thermal efficiency.

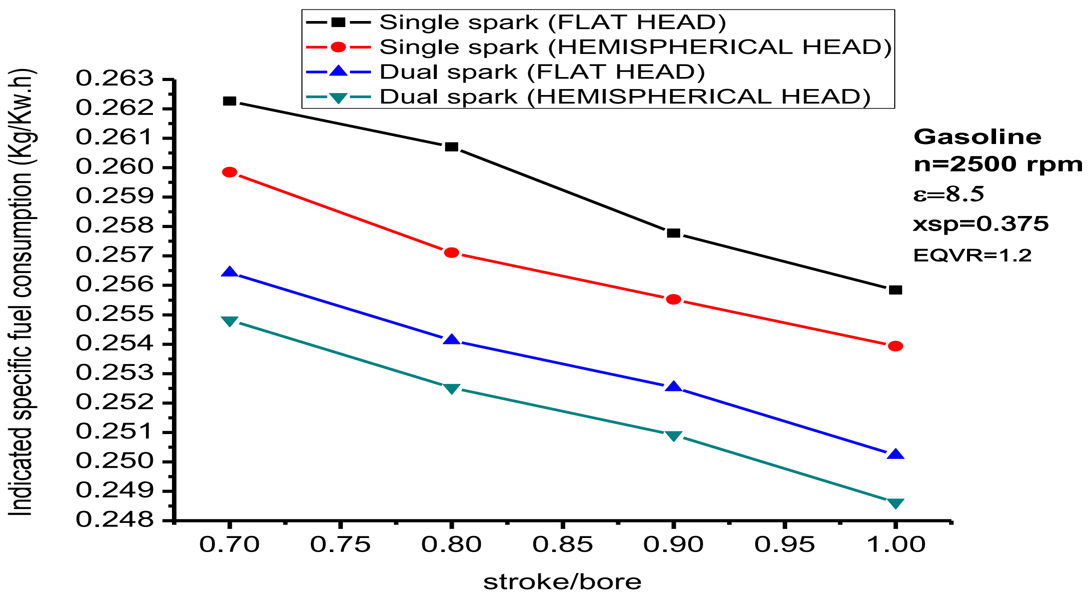


Figure11. Indicated specific fuel consumption versus stroke/bore ratio

INDICATED POWER:

Indicated power is an important parameter because it is independent from the engine dimensions and used to improve correlations for engine operation, especially engine friction. The comparison of the indicated power versus cylinder diameter is shown in Figure 12 . As seen from the figure, the values of indicated power rise as the cylinder diameter decreases with a decreasing manner for all spark locations. Additionally, dual plug (hemispherical head engine) has slightly higher values than single plug (flat head engine) as well as dual-plug position (flat head engine) for same spark plug position. It is noted here that the use of dual-plug configuration has obviously an advantage as the cylinder diameter decreases compared to the single plug. According to figure dual spark plug (hemispherical head engine) gives 8% greater value of indicated power than single plug (hemispherical head engine) and 8.8% greater value of indicated power than single plug (flat head engine) at stroke/bore ratio=0.9.

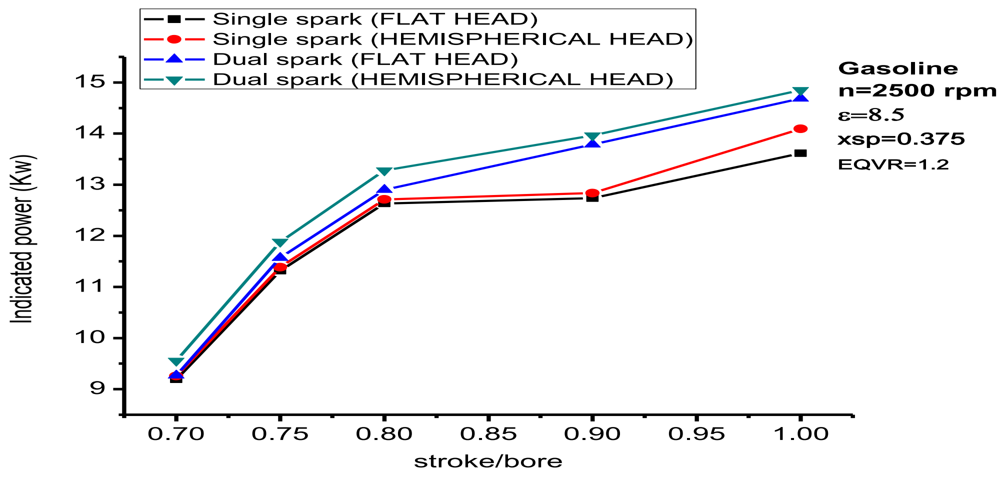


Figure 12. Indicated power versus stroke/bore ratio

BRAKE POWER:

The comparison of the Brake power versus cylinder diameter is shown in Figure 13 . As seen from the figure, the values of brake power rise as the cylinder diameter decreases with a decreasing manner for all spark locations. dual plug (hemispherical head engine) has slightly higher values than single plug (flat head engine) as well as dual-plug position (flat head engine) for same spark plug position.. It is noted here that the use of dual-plug configuration has obviously an advantage as the cylinder diameter decreases compared to the single plug. According to figure dual spark plug (hemispherical head engine) gives 9% greater value of indicated power than single plug (hemispherical head engine) and 9.4% greater value of indicated power than single plug (flat head engine) at stroke/bore ratio=0.9.

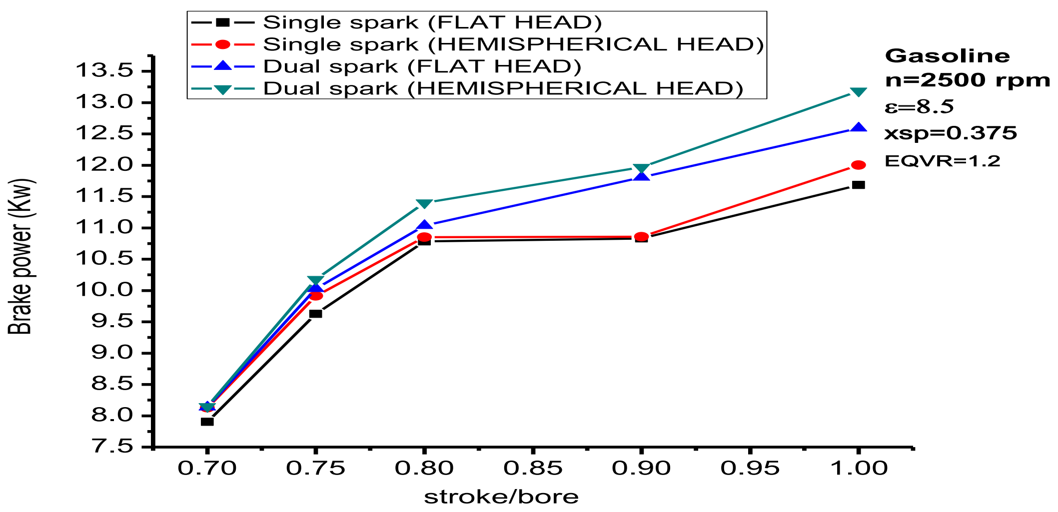


Figure 13. Brake power versus stroke/bore ratio

8. CONCLUSIONS

The performance of an SI engine having twin-spark ignition system with hemispherical shaped combustion chamber and flat head combustion chamber has been investigated. For this purpose, a quasi-dimensional SI engine cycle model has been used. The effects of variations of spark plug locations on engine performance have been investigated . Comparisons were also made to the single-spark engine for both flat head combustion chamber and hemispherical head combustion chamber for the same conditions. The following conclusions can be drawn in the light of results obtained:

The presented model has ability for computing the SI engine cycles for both the cases of operating with single- and twin spark plugs.

The centrally located single-spark configuration for both flat head combustion chamber and hemispherical head combustion chamber gives the best performance and fuel economy in comparison to all other configurations.

If central location of spark plug is not possible because of the some design constraints because of this, twin-spark plug configurations can be preferred. It was obtained that the twin-spark configurations (hemispherical head) give better performances and fuel economy than single-spark configurations for all spark plug locations, except centrally located single-spark configuration. This is a result of faster burning and lower heat losses achieved by twin-spark engines in comparison to single-spark engines.

Dual plug operation also improves the engine performance at different percentages for examined S/B ratios. Especially, performance improvements with dual plug are obtained dramatically for little S/B ratio. The increment with the dual plug (hemispherical head) for S/B = 0.9 in indicted mean effective pressure and indicated power are about 2% and 8% compared to single plug (hemispherical head) and are about 4.3% and 8.8% compared to single plug (flat head) at rsd =0.375 respectively.

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