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# Numerical Analysis of Alternative Power Output of Spark Plugs on Engine Performance and Emission Using Ricardo Wave.

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**ABSTRACT**
Emission released from the internal combustion engines run on fossil fuels which contain hydrocarbon (HC). Normal combustion products of any IC engines are Carbon dioxide ($CO_2$), water ($H_2O$) and Oxides of nitrogen ($NO_2$) in the complete combustion process of engine. These exhaust products are not considered as a pollutant but some additional products such as unburned hydrocarbon (HCs), carbon monoxide (CO), nitrogen oxide (NOx) and particulate matter (PM) create the most harmful effect on the environment as well as human. The quest to reduce these pollutants led to various technics such alternative fuels, spark plug positions and so on. The work focused on alternating the power of the spark plug and analyzing the performance of the engine and its related emission. The outcome realized was that the alternating powers of the spark plug for 30 W and 30KW did not really so much change the performance of the engine with a given set of parameters. Ricardo Waves was used for the simulation after the 2014 edition of SolidWorks was used for the geometry development. The work unveiled the fact that improved engine performance leads to low emissions and vice versa. Further research should gear towards the brackets of parameters within which alternating the power of the spark plug influences engine performance and emission.
**Key Words**: Alternating, Power output, Spark plug, Engine performance

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## I. INTRODUCTION

Most of the Internal Combustion (IC) engines run on the fossil fuel which contain hydrocarbon (HC). Normal combustion products of any IC engine are Carbon dioxide (CO2), water (H2O) and Oxides of nitrogen (NO2) in the complete combustion process of engine. These exhaust products are not considered as a pollutant because they do not cause direct hazard on human. But normally in real combustion process some additional products such as unburned hydrocarbon (HCs), carbon monoxide (CO), nitrogen oxide (NOx) and particulate matter (PM) also appears. These products create the most harmful effect on the environment as well as human. Quantity of this harmful product of Spark Ignition (SI) engine is five (5) times more than that of Compression Ignition (CI) engine.

Aside these, the legal requirements (emission standards) governing air pollutants (oxides of nitrogen (NOx), Oxides of Sulphur (SOx), carbon monoxide (CO), Hydro carbons (HC) and several others) released into the atmosphere, not excluding emissions emanating from automobiles and other powered vehicles, have given room to a wide range of research in the area of emission control.

Information surfed from Wikipedia (en.wikipedia.org) on Vehicle emission standard revealed that the first automobile emissions standards were enacted in 1963 in the United States, mainly as a response to Los Angeles' smog problems. Three years later according to the site, Japan enacted their first emissions rules (in 1966), followed by Canada, Australia, and several European nations between 1970 and 1972. The early standards mainly concerned carbon monoxide (CO) and hydrocarbons (HC). Regulations on nitrogen oxide emissions (NOx) were introduced in the United States, Japan, and Canada in 1973 and 1974, with Sweden following in 1976 and the European Economic Community in 1977. These standards gradually grew more and more stringent but have never been unified.

The research is further widened and geared towards fuel economy, combustion efficiency amongst other related but relevant topics aside emission control. This has led to the introduction of multi spark plugs on single cylinders as well as multi spark plugs on each cylinder of multi-cylinder engines as a measure of controlling emissions by the improvement of fuel economy (Bozza et al, 2004).

A U. S. Patent produced in August 9th 2011 depicts a system and method for operating a multiple cylinder internal combustion engine having at least two

spark plugs per cylinder include a first control wire coupled to a first spark plug of a first cylinder and a second spark plug of a second cylinder, and a second control wire coupled to a second spark plug of the first cylinder and a first spark plug of the second cylinder with the first and second spark plugs of the first cylinder being selectively fired during the power stroke of the first cylinder and the first and second spark plugs of the second cylinder being selectively fired during the power stroke of the second cylinder to provide individual control of each spark plug using a number of control lines less than the number of spark plugs.

Even though the first automobile emissions standards were enacted in 1963 in the United States and other countries followed suit, today, emission from automobile and other power vehicles is still a challenge that requires an optimum solution. This has called for researchers across the globe especially in the automobile engineering field to delve deep into finding a lasting solution to this challenge of the century so as to reduce the emissions from automobile and their related causes.

One of the best methods to improve the engine performance and reduce the exhaust emission in a SI engine is by the introduction of twin spark into the combustion chamber Khan & Shaikh, (2019). Experiments were conducted at different load conditions and different types of engines have proved that dual spark plug ignition engines are surely better than a single spark plug engine.

Narsimha Bailkeri et al., (2015) has shown that introduction of dual spark ignition has considerably increased the performance of the engine by increasing efficiency & power and reducing its exhaust emissions. Same results can also be seen in the study done by Ajay K. Singh et. al proved that dual spark ignition system is better for improving ignition process even in 2-stroke engines. Thus, reviews and studies have clearly indicated that use of multiple spark ignitions can increase the rate of combustion by rapidly completing the process (Khan & Shaikh, 2019).

## II. MATERIAL AND METHODS

This section provides information on the materials and methods used in the execution of the main agenda of the thesis which is the numerical analysis of multiple spark plugs and the related emission. The work zooms into the selected tool for the investigation carried out in ascertaining the effect of alternate spark plugs power on the performance of the engine in relation to its emission when the spark plugs power per cylinder is altered.

### A. MATERIALS

The Ricardo Wave Software (RWS) is the tool selected for this work from the many numerous tools (Computation Fluid Design (CFD), Analysis systems (Ansys), Engine forte, AVL) available that are capable in the simulation process. The chosen tool is a state of the art one dimension (1D) gas dynamics simulation. It is used worldwide in industry sectors including ground transportation, rail, motor sport, marine and power generation. WAVE enables performance and acoustic analyses to be performed for virtually any in-take, combustion and exhaust system configuration. Also, it is used throughout the engine design process because it is the ideal tool for things such as improving volumetric efficiency, designing complex boosting systems, improving transient response or extracting the maximum performance from a race engine. This makes wave more suitable for the workpiece as compared to other simulation tools readily available.

WAVE simulation software solves the 1D form of the Navier-Stokes Equations (NSE) governing the transfer of mass, momentum and energy for compressible gas flows, and includes sub-models for combustion and emissions.

For Compressible fluids, the (isentropic) compressible Navier-Stokes equation is given as:

$$\partial t(\rho u) + \mathrm{div}(\rho u \otimes u) + \nabla p(\rho) = \mathrm{div}\, S(\nabla u)\ \partial t\rho + \mathrm{div}(\rho u) = 0, \quad (1)$$

Where, S denotes the Newtonian stress tensor, and the pressure is now a constitutively given function of the density (e.g. the polytropic pressure law $p(\rho) = \rho\ \gamma$ , $\gamma > 1$ the adiabatic exponent).

The use of Ricardo WAVE to develop engine simulations requires several computer programs that vary in purpose from model setup and 3-Dimensional (3D) modeling, to statistical analysis of model output. The four (4) programs used in this research are:

1. Wave Build
2. Wave Mesher
3. Wave Solver and
4. Wave Post.

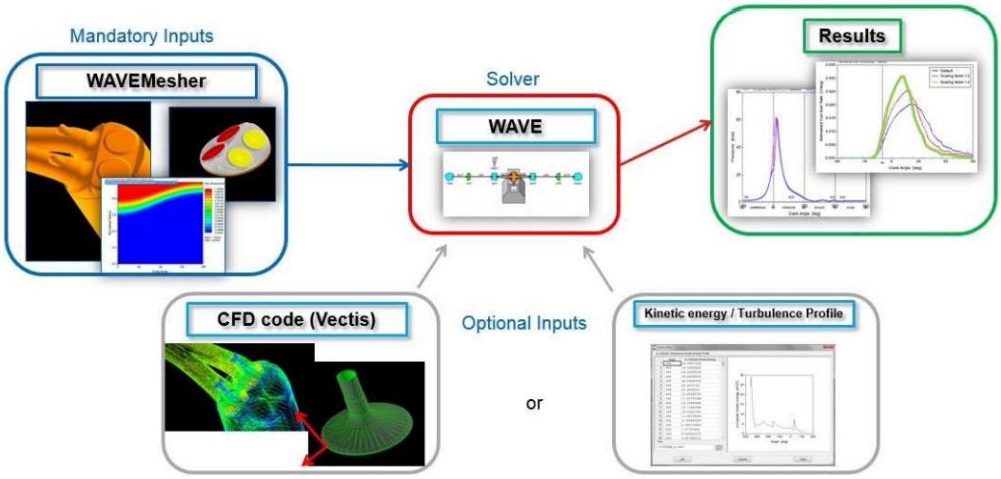


**Figure 1 A general flow diagram for the development of the model used in the work.**

The first mandatory inputs into Wave Mesher as captured in Figure 3.1. An stl file from the engine geometry is needed. The engine geometry was developed using the 2014 edition of SolidWorks.
In SolidWorks, the various parts of the engine such as the cylinder, piston, valves and the spark plug were all designed. The various dimensions of the components are used in the software to first produce the individual components and afterward assembled together to produce a gas tight combustion chamber (engine). The fully assembled geometry is captured in Figure 3.2.

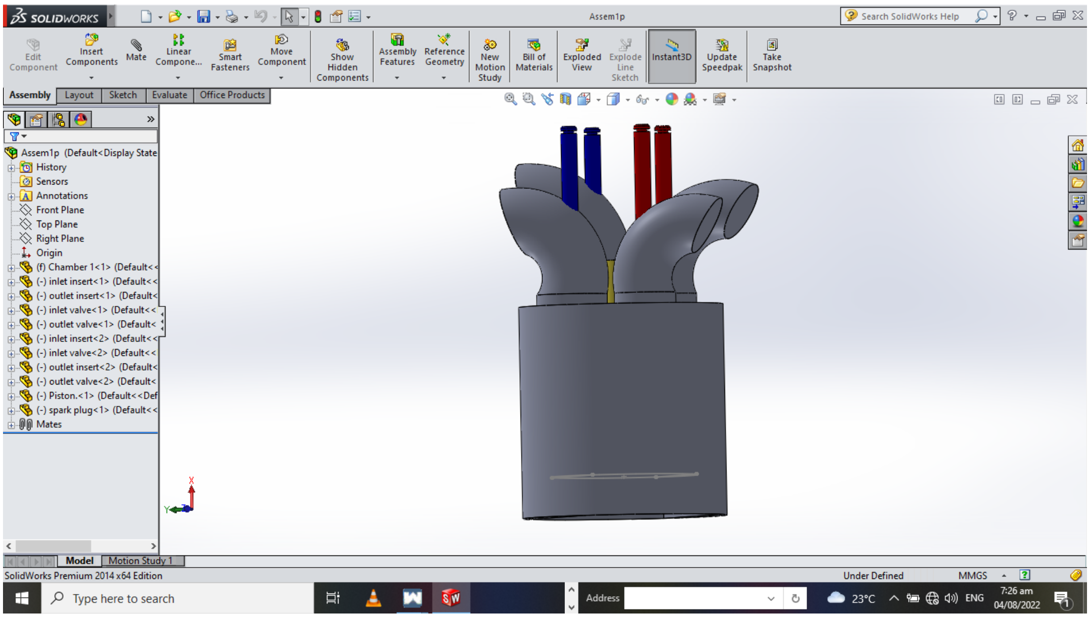

**Figure 2 A geometry of cylinder and assembled components**

The dimensions of the geometry so designed by Solid Works are captured in Table 1. It is this geometry that is converted to an stl file which is in-turn used in Wave Mesher to further produce a combustion module as can be seen in the aspect covered by the Wave Mesher in the Ricardo software.

**Table 1 Elements and their values used for the module**

| ELEMENT | VALUE (mm) |
|---|---|
| Cylinder bore | 85 |
| Stroke | 80 |
| Connecting rod length | 150 |
| Compression ratio | 10:1 |
| Inlet manifold (Left diameter) | 40 |
| Inlet manifold (Right diameter) | 35 |
| Inlet manifold (Length) | 100 |
| Inlet port (Left diameter) | 35 |
| Inlet port (Right diameter) | 35 |
| Inlet port (Length) | 50 |
| Exhaust port (Left diameter) | 28 |
| Exhaust port (Right diameter) | 28 |
| Exhaust port (Length) | 90 |
| Exhaust manifold (Left diameter) | 28 |
| Exhaust manifold (Right diameter) | 40 |
| Exhaust manifold (Length) | 150 |

The same dimensions used on the geometry are also used in Wave Build. A graphical Interface of Wave Build is captured in Figure 3

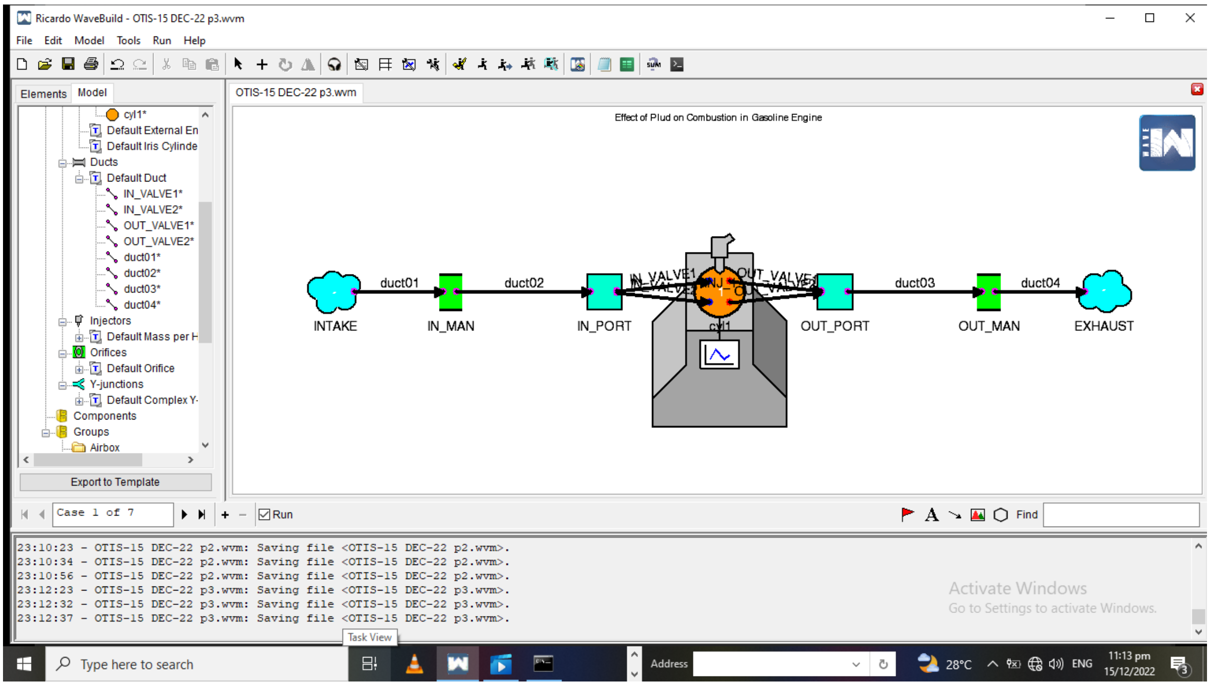


**Figure 3 A single cylinder Wave Build GUI Engine**

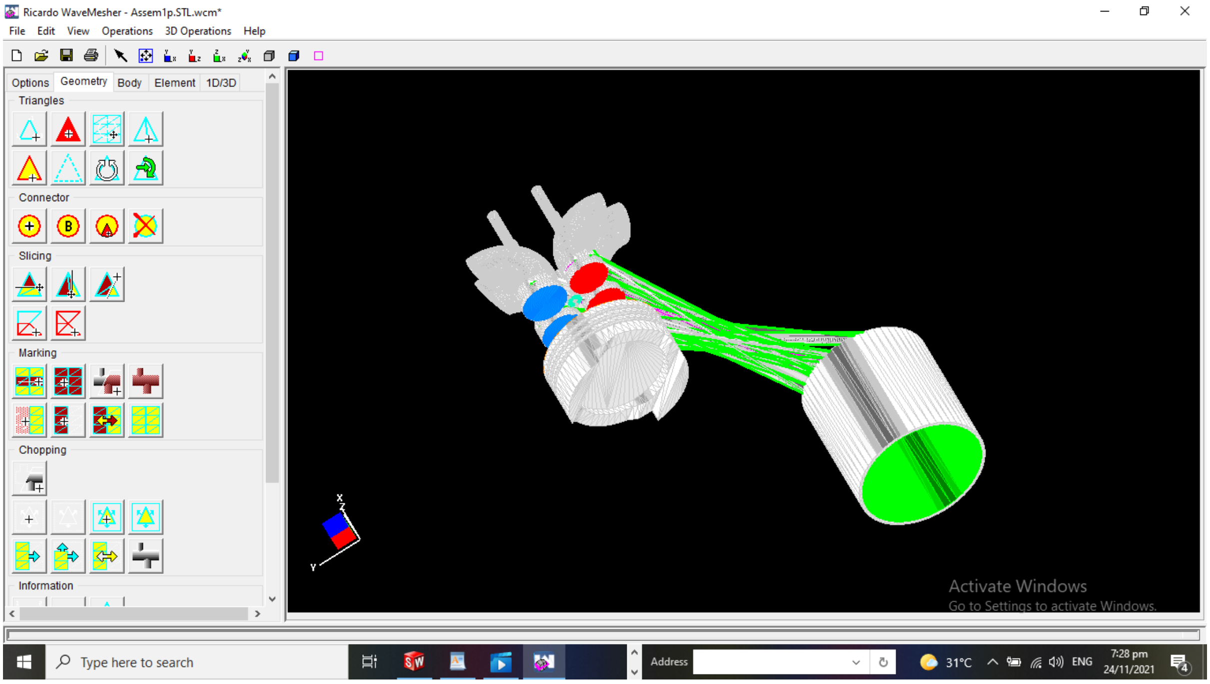


**Figure 4 Wave Mesher**

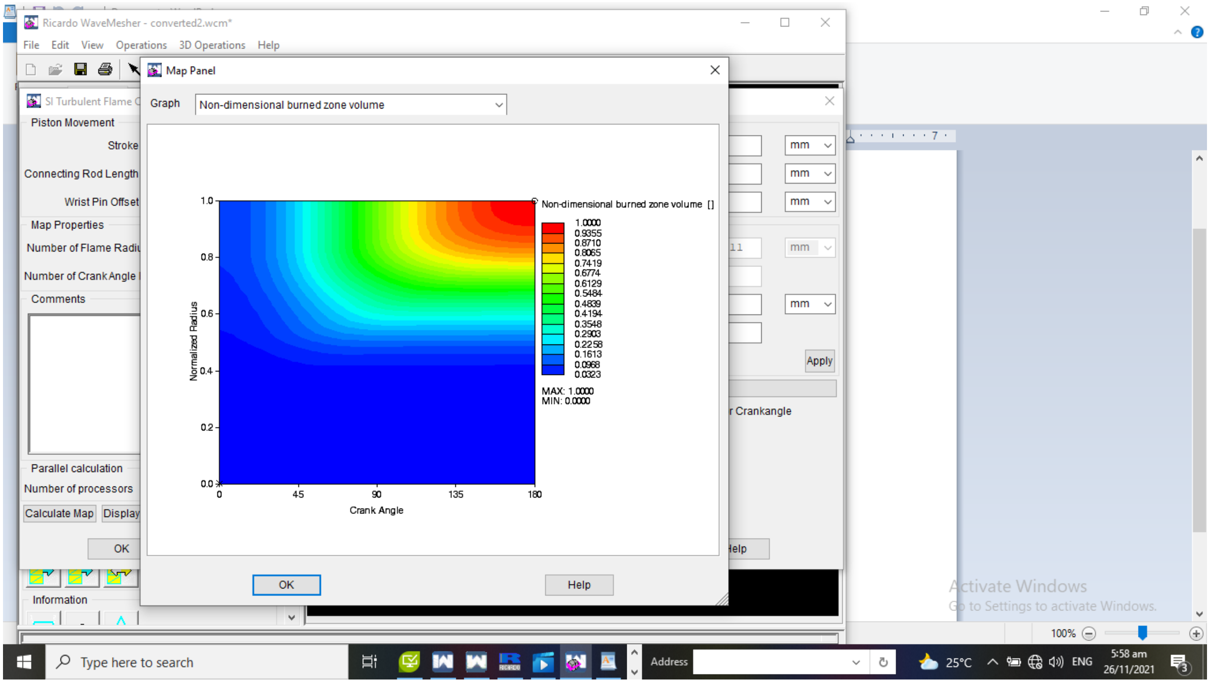


**Figure 5 Generated Combustion module success graphical symbol**

## B. METHOD FOR ROAD MAP

Wave Build allows complex geometries to be imported into the model from 3D CAD files using a program called Wave Mesher. Wave Mesher allows the end user to manipulate 3D CAD models of complex geometries such as intake manifolds and exhaust headers, so that the 3D models can be broken-down into a usable one-dimensional (1D) form for the WAVE processor. Figure 4 is a screen shot of the Wave Mesher program in which an engine geometry in Figure 2 is developed by Solid-Works 14 and converted to a .stl file has been meshed for use in Wave Build.

Some of the files generated by wave Mesher and used in Wave Solver after Designing Wave Build are the Combustion SDF file containing the turbulent flame burn maps (.tfbr). This file is generated by the Wave

Mesher program for the purpose of the combustion set up. If the combustion module is properly developed without any form of error, the interface shown in Figure 5 is produced. The Figure shown is just a sign of successful development of a file with an extension known as the combustion module file.

Once the model is setup in Wave Build and 3D models have been meshed, a simulation can be started by running the WAVE code. WAVE is the solver that performs all the calculations needed to simulate engine operation. It is a non-interactive program that runs in a DOS window while streaming certain output data and simulation progress. The out-put data shown during simulation runtime can be customized to show parameters of interest. These parameters can be used as indicators to show whether or not the simulation is producing reasonable results, allowing the simulation to be prematurely stopped if the model is not functioning properly.

With WAVE Solver, all the conditions for the advancement of the simulation are given (entered) after the necessary parameters are entered and it is set to run. Once a simulation is finished, a large output file is created that contains all data needed to analyze the simulated engine operation.

Wave Post is the post-processor for WAVE simulations that allows interpretation of simulation results. It allows for the creation of: time plots, sweep plots, spatial plots (ani-mated), and TCMAP plots (for turbines and compressors).

The engine model is setup by defining some relatively basic inputs and then some more advanced inputs that require some engine testing. The basic inputs are composed of engine geometry and boundary conditions. Therefore, all dimensions from the intake and exhaust ducting must be recorded and input (refer to Table 1). Likewise, manufacturer specifications for internal engine geometry such as bore, stroke, connector rod length, wrist-pin offset and compression ratio must be input. Initial conditions such as exhaust temperatures, intake temperatures, and wall temperatures need to be input as reasonable values. These can be modified to higher accuracy once actual engine measurements be-come available.

## C. COMBUSTION MODULES

### SI Wiebe Combustion

The SI Wiebe function is widely used to describe the rate of fuel mass burned in thermodynamic calculations. This relationship allows the independent input of function shape parameters and of burn duration. It is known to represent quite well the experimentally observed trends of premixed SI combustion. It is a primary combustion model and the most commonly used combustion sub-model in SI engines. It can be applied to all engine cylinder elements. A list of all the available time plots from the SI Wiebe combustion sub-model is shown in Table 2.

**Table 2 SI Wiebe time plots**

| Plot # | Plot Title |
|---|---|
| 146 | Combustion Fuel Burn Rate |
| 147 | Cumulative Combustion Fuel Burned |
| 148 | Combustion Heat Release Rate |
| 149 | Cumulative Combustion Heat Release |
| 154 | Instantaneous Combustion Equivalence Ratio |

The equation for Wiebe module is defined by

$$W = 0.1 \exp\{ - AWI\ (\Theta^{0}/BDUR)\ (WEXP+1) \} \quad (2)$$

where: W = Cumulative mass fraction burned

AWI = Internally calculated parameter to allow BDUR to cover the range of 10-90%

$\Theta^{0}$ = Degrees past start of combustion

BDUR = User-entered combustion duration (10%-90%)

WEXP = User-entered exponent in Wiebe function

The burn profile in the input panel can be used to observe the effects of varying the input parameters. Varying the 50% burn point simply shifts the entire curve forward or back-ward. Varying the 10%-90% duration will extend the total combustion duration, making the profile extend longer or compress shorter. Varying the Wiebe exponent will shift the curve to burn mass earlier or later.

### SI Turbulent Flame Combustion

The SI Turbulent Flame combustion sub-model is a predictive combustion model for port-injected or early direct-injected, pre-mixed (spark-ignition) engines. The combustion sub-model includes various options for flame propagation at various levels of complexi-ty. The sub-model also includes options for spark enhancement. It is a primary combus-tion model and can be applied to all engine cylinder elements in an SI engine. It must be used in conjunction with one of the Turbulence and Flow sub-models.

The turbulence velocity is calculated as:

U’ ¬ = Cprop x Upiston (3)

where: Cprop = User-entered ratio of turbulence velocity to mean piston speed

Upiston = Mean piston speed

Both measurements and CFD calculations for turbulent flows in the engine suggest that the turbulence length scale, L, varies gradually from a smaller value at TDC to a larger value at BDC. The turbulence length scale is varied sinusoidally as:

L = ½ ((LBDC + LTDC ) – (LTDC - LBDC )cosαe ) (4)

where: LTDC = User-entered integral length scale at TDC

LBDC = User-entered integral length scale at BDC

αe = Engine crank angle [rad]

The user-entered profile of turbulence velocity is used directly but for the “Turbulence Kinetic Energy Input” option, the user entered profile of turbulence kinetic energy is converted to a profile of turbulence velocity by the following equation:

Equation (4) U' ¬ = √ ⅔K

where: k = User-entered values of turbulent kinetic energy

Both measurements and CFD calculations for turbulent flows in the engine suggest that the turbulence length scale, L, varies gradually from a smaller value at TDC to a larger value at BDC. The turbulence length scale is varied sinusoidally as:

L = ½ ((LBDC + LTDC ) - (LTDC - LBDC )cosαe ) (5)

where: LTDC = User-entered integral length scale at TDC

LBDC = User-entered integral length scale at BDC

αe = Engine crank angle [rad]

By default, Spark-Ignited combustion models in WAVE follow a constant combustion air/fuel ratio under the assumption that the fuel-air mixture is fully premixed. In certain spark-ignited engine designs (primarily Spark Injection Direct Ignition), the fuel and air are not fully mixed at the start of combustion. To alter the combustion stoichiometry and allow WAVE to adapt to mass added or removed from the cylinder during SI combustion, a stratified charge secondary combustion model can be activated. The model allows the user to specify a combustion equivalence ratio to be used during the early part of combustion.

## III. RESULTS AND DISCUSSIONS

This part takes a close look at the results gathered from the modules and tools outlined in chapter three. Ricardo Wave Post is the model used in accessing the results generated in large files. The generated data is outlined and then analyzed subsequently based on the Performance.

**PERFORMANCE**

Under this section, a good number of performance related results generated are displayed and each of those relevant ones relating to the performance of the engine discussed. The results generated concentrates on the use of the Wiebe Combustion Model as the base model alongside the use of the Turbulence Flame Model of which the spark plug power of 30W and 30KW are used. The tables and graphs that follow, gives a clear picture of the performance of the engine as captured by the results of those models considered. In all, what is considered is the comparative performance of the Wiebe viz a viz the Turbulence module of 30W and 30KW of spark plug power to ascertain the one under which maximum engine performance is achieved.

1. **Brake Torque.**

The values for brake torque are displayed in Table 4 Even though there are variations in the values of both the 30W and 30KW power of the spark plug, the variations are insignificant. The peak of the power for both Spark plug powers and Wiebe is at a speed of 4500 RPM with the values being 168.30 and 165.80 respectively. Both build their power from a lower value to the peak point as mentioned earlier but declines from the peak point till the 6000 RPM mark of engine speed.

**Table 3 Brake Torque vs Engine Speed**

| BRAKE TORQUE (NM) VS ENGINE SPEED (RPM) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| WIEBE | 143.44 | 150.00 | 151.56 | 159.68 | 155.30 | 165.60 | 164.00 | 165.80 | 158.10 | 139.37 | 125.30 |
| SPARK POWER (30W) | 104.00 | 127.32 | 141.00 | 155.60 | 156.50 | 169.26 | 167.30 | 168.70 | 155.60 | 130.24 | 108.78 |
| SPARK POWER (30KW) | 104.00 | 127.32 | 141.00 | 155.60 | 156.10 | 169.26 | 167.32 | 168.30 | 155.60 | 130.22 | 109.26 |

As can be seen clearly in Figure 1, the Wiebe module which is a standard module for combustion, records a higher engine performance than the turbulent module for both powers of the spark plug. Even though the blue curve is what is seen, it is worth mentioning that the yellow curve represented by the spark power of 30W is over shadowed. Reference may be made to table 1 for clarity in terms of the values.

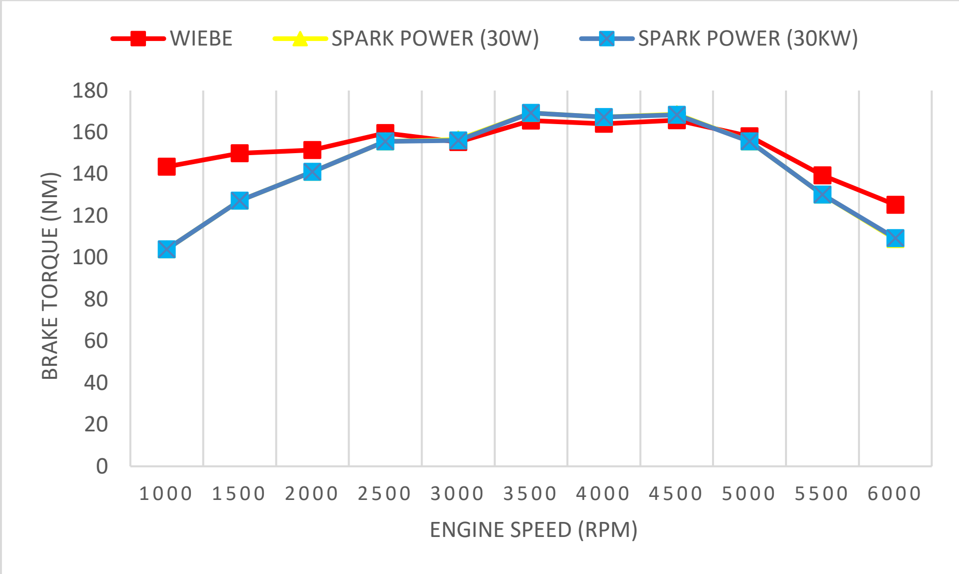


**Figure 6 Brake Torque vs Engine Speed**

### 2. Brake Power

Table 4 illustrates the brake power of the engine which is a function of the power generated by the engine as compared to the spark plug power of 30W and 30KW. The Wiebe module registers high values than that of the increase in the spark plug power. This significantly suggests that the varied spark power of the plug has a zero or no effect on the performance of the engine relating to the brake power.

**Table 4 Brake Power vs Engine Speed**

| BRAKE POWER (KW) VS ENGINE SPEED (RPM) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| WIEBE | 14.64 | 23.75 | 31.75 | 42.09 | 48.8 | 61 | 68.93 | 77.47 | 82.35 | 79.91 | 78.69 |
| SPARK POWER (30W) | 10.37 | 20.13 | 29.28 | 40.87 | 49.41 | 62.22 | 70.76 | 79.3 | 81.13 | 75 | 68.32 |
| SPARK POWER (30KW) | 10.35 | 19.52 | 29.28 | 40.87 | 49.41 | 62.22 | 70.15 | 78.69 | 84.13 | 75.64 | 68.93 |

Between the speed of 2000 RPM to 3500 RPM the influence of spark plug power is the same but rather varied slightly in favour of 30W in the beginning and in favour of 30KW in the end at speeds above 5000 RPM. It is also realized from Table 4.2 that at a speed of 5000 RPM, the performance of the engine declines. Indeed, the power of the spark plug to an extent increases the performance of the engine but not at all speeds.

### 3. Indicated Torque

From the graph of Indicated Torque versus Engine Speed in Revolutions per Minute in Figure 7, it is observed that the power remains constant at speeds of 3500, 4000 and 4500 RPM but declines afterwards at speeds of 5000 to 6000 RPM on the part of the 30W power of the spark plug power for Turbulence. It is noted that the Wiebe also records a decline of indicated torque at the same speeds of 5000 to 6000 as that of the spark plug powers. Whereas that of the values for the plug powers are 185.30, 163.41 and 143.90, the values for Wiebe are 188.75, 172.50 and 161.56 respectively.

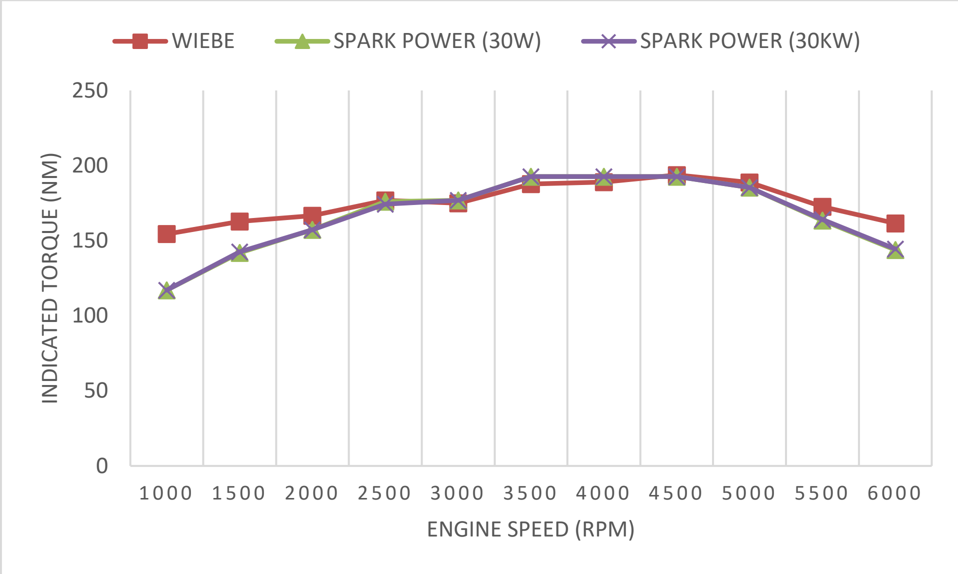


**Figure 7 Indicated Torque vs Engine Speed**

### 4. Indicated Power

Here, it is observed that the curves of both plug powers at 30W and 30KW rises steadily from 16.07 at a speed of 1000 RPM to 130.36 which is 5000 RPM and then slopes to 121,43 at a speed of 6000 RPM. The Wiebe module on the other hand rises from 21.78 through to 138.75 at a speed of 6000 as it can be seen in Figure 8. The implication of this shows that at a speed beyond 5000 RPM, there can be no improvement of the engine's performance with the given parameters and conditions remaining the same.

Table 5 Indicated Power (hp) vs Engine Speed (RPM)

**Table 5 Indicated power vrs Engine Speed**

**Indicated Power (hp) vs Engine Speed (RPM)**

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 30kw | 16.07 | 30.35 | 43.75 | 61.60 | 75.00 | 94.64 | 108.03 | 124.11 | 130.36 | 125.8 |
| 30w | 16.07 | 30.35 | 43.75 | 61.60 | 75.00 | 94.64 | 108.03 | 125.00 | 130.35 | 125.5 |
| WIEBE | 21.78 | 36.96 | 48.03 | 62.67 | 76.96 | 95.17 | 107.14 | 123.57 | 126.07 | |

0 TO 150 FOR 30KW @ INT 25, 0 TO 150 FOR 30W @ INT 25, 20 TO 140 FOR WIE

20

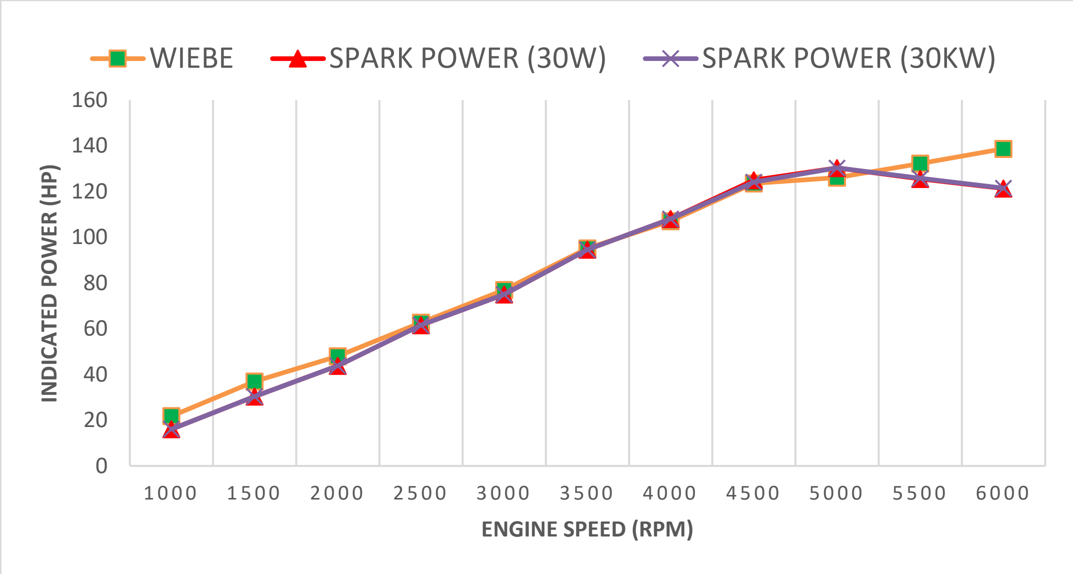


**Figure 8 Indicated Power vs Engine Speed**

### 5. Brake Thermal Engine Efficiency

For the brake thermal engine efficiency, all the values obtained for both the 30W and 30KW of spark plug power as captured in Table 4.4 are the same with no single variation. Together, the values start from 19.5 at an engine speed of 1000 RPM, and rises to 27.25 at a speed of 3500 RPM. It them falls from there to 19.80 at a speed of 6000 RPM. This gives a curved shape of both 30W and 3 KW spark plug power. As compared to the Wiebe module, the rise is only from 26.90 to 27.50 from which it declines to 25.565 at 3500. It then rises sharply to 26.25 at 4000 RPM and then falls to 22.80 at a speed of 6000 RPM. In all, the efficiency of the engine performance in terms of brake thermal engine, is slightly higher in the Wiebe module which is a standard Spark Ignition model as compared to the increase in the power of the Spark Plug in the case of both the 30W and the 30KW.

Table 4.4 Brake Thermal engine efficiency (%) vs Engine Speed (RPM)

**Table 6 Brake Thermal Efficiency vrs Engine speed**

| Brake Thermal engine efficiency (%) vs Engine Speed (RPM) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 30KW | 19.50 | 23.25 | 25.25 | 26.25 | 27.00 | 27.25 | 26.30 | 25.80 | 24.25 | 22.25 |
| | 1000 | 1500 | 2000 | 2500 | 3000 | 3500 | 4000 | 4500 | 5000 | 5500 |
| 30W | 19.50 | 23.25 | 25.25 | 26.25 | 27.00 | 27.25 | 26.30 | 26 | 24.25 | 22.25 |
| WIEBE | 26.90 | 27.50 | 27.50 | 27.35 | 26.90 | 25.65 | 26.25 | 25.50 | 24.75 | 23.75 |
| 18 to 28 | | | | | | | | | | |

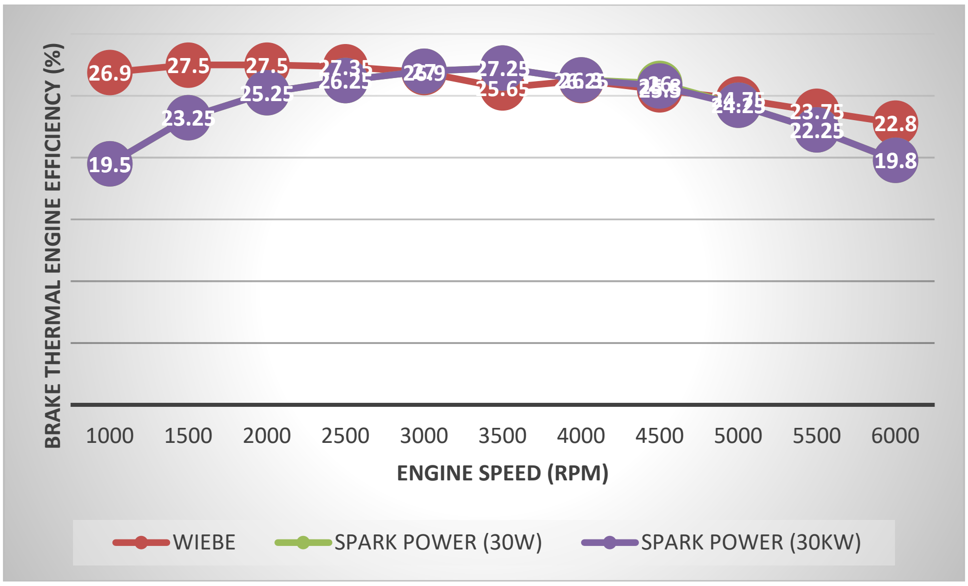


**Figure 9 Brake Thermal engine efficiency vs Engine Speed**

## IV. DISCUSSION AND CONCLUSION

From the discussion so far, it has come to light that the alternating powers of the spark plug has an effect on the performance of the engine and its related emission. However, under certain conditions including high temperatures, the increase in the power or output of the spark plug becomes insignificant, which can also be said to be a negative effect due to power losses, since the increase does not positively impact the performance of the engine.

Again, the Wiebe model which is the standard model in this research work has a high performing rate comparatively to the Turbulent model within specified conditions. The performance index may change significantly with change in conditions.

The spark plug should literally be inserted in the cylinder head and made to operate at the same time and the performance of the engine ascertained.

Different performance conditions should be captured and tested in order to find the conditions under which the performance index can be increased.

Tests should be carried out on different makes and capacities of engines to discover if the makes and capacities of the engine has any influencing factors on the performance of the engine and its related emission.

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