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Influence of Combustion Chamber Design Parameters and Intake Environments on Spark Ignition Engine Performance and Exhaust Gas Emission

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Abstract

In the present paper, the effect of the combustion chamber design parameters on the improvement of combustion efficiency (the heat generated inside the combustion chamber) and the enhancement in the pollution rates (heat emissions) from a four-stroke, spark-ignition engine has been studied experimentally and theoretically. Two different programs, Gaseq and Ansys, were used to simulate the effect of the combustion chamber shape, turbulent kinetic energy, intake temperature, intake pressure, parity ratio, compression ratio, and engine speed on reducing specific fuel consumption in the engine, reducing carbon dioxide emissions, and increasing overall engine efficiency. The results showed increasing the intake temperature increased the amount of heat produced in the combustion chamber. This leads to increases in the overall efficiency of the engine, but leads to increasing the carbon dioxide and nitrogen oxide emissions. Increasing the intake pressure has a positive effect on the combustion temperature and pressure, but it has a negative effect on carbon dioxide and nitrogen oxides. Raising the pressure ratio improved the overall efficiency of the engine by increasing the combustion heat, but increasing specific fuel consumption and emissions. Also, increasing the engine speed above the permissible limit has an adverse effect on the spraying speed due to the piston speed being higher than the flame speed, which leads to a reduction in the engine brake torque. An increase in the compression ratio leads to higher fluid pressure and output capacity, but combustion methods occur. An increase in the kinetic energy of the turbulence leads to good combustion. A bowl in a piston has the highest rate of rotation and rotation compared to flat and hemispherical pistons. That is, the design of the cylinder head of this type leads to an improvement in the combustion efficiency and thus the efficiency of the engine.

Keywords

Spark Ignition Engine, Four Stroke, Combustion Chamber, Crank Angle, Emission

1. Introduction

Nowadays, with modern measuring devices in laboratories and modern numerical software, and from newly published research [1]-[10], it has been found that to achieve the highest efficiency of the spark-ignition engine, the combustion process must be complete within the combustion chamber. This requires controlling the conditions of the air entering the engine and also designing the combustion chamber very carefully to achieve the highest efficiency [11] [12] [13] [14]. On the other hand, it was found that the low pressure inside the engine leads to a decrease in the combustion chamber, which leads to the consumption of more than specific fuel [8] [9] and thus leads to a decrease in the engine inefficiency. While the emission of nitrogen oxides increases when the pressure decreases [15] [16] [17]. Also, the temperature of the air entering the engine is one of the regulating factors for controlling and improving the combustion because it affects the start of the combustion timing and the combustion duration. The higher inlet air temperature increases combustion start-up and reduces the volumetric efficiency of the engine [18]. Ramesh *et al.* [19] conducted experiments on a homogeneous charge pressure combustion engine using acetylene as a fuel. The inlet air was heated to different temperatures to determine the optimum level of the range between 40˚C and 110˚C. The engine brake thermal efficiency was found to improve as the intake air temperature increased, and nitric oxide and smoke levels were reduced. Zhao and others [20] studied the effect of some factors that affect engine efficiency, such as the shape of the combustion chamber and fuel-air ratios, on improving fuel economy and reducing emissions. Improving fuel consumption with lower exhaust emissions gives more focused to all car manufactures [21] [22] [23] [24]. Melih and Bilge [25] studied the effects of spark-ignition engine's different variables on engine performance and emissions experimentally. Theoretical [26] [27] analyses were performed on a spark-ignition engine to determine the response of a pre-mixed flame as a result of changing the intake pressure and temperature and the valence ratio in basic parameters related to particle formation.

In this paper, to detect the effect of the inlet pressure and temperature on the engine performance and exhaust gas emission Gaseq program was used in the theoretical part. For the present experimental work, a complete test facility, a four-stroke, single-cylinder, spark-ignition engine, equipped with all measurement equipment was used. The results were observed for the temperatures and pressures inside the combustion chamber and at the engine outlet, emission ratios. The equivalence ratio is defined as the air/fuel ratio for complete combustion on the sprocket over the air/fuel ratio for incomplete combustion on the sprocket which can be calculated by balancing the fuel and air chemical composition for complete and incomplete combustion.

2. Experimental Setup and Test Results

The testbed as shown in **Figure 1**, consisted of a 305CC, four-stroke, single-cylinder, air-cooled, spark-ignition engine (Briggs & Stratton) with a maximum power of 7.1 kW at 3600 rpm. One end of the motor shaft is coupled to an eddy current dynamometer to apply the load and the dynamometer is manually controlled to vary the load on the motor. An electric heater is installed in the engine suction tube, and the inlet air temperature can be changed through the electronic control unit. The load applied to the motor is shown in newton-meters on the digital meter. The engine speed is shown in a digital counter on the control panel. The inlet and outlet temperatures of the engine cooling water are measured using thermocouples, the exhaust gas temperature by using a thermal sensor. These sensors are connected to the system control panel, and the readings are displayed on a digital counter. The AVL Di-gas analyzer is used to measure the engine exhaust emission as CO, HC, NOx, CO_2, and O_2. The measured uncertainty in specific fuel consumption is ±1.5%, brake power ±0.5%, brake thermal efficiency ±1%, NO emission ±4.1%, CO emission ±1.5%.

Figure 2 shows the effect of inlet temperature on the spark ignition engine brake thermal efficiency at different brake mean effective pressures. In general, the brake thermal efficiency increases with increasing the engine brake mean effective pressure due to increases of the heat generation inside the combustion chamber. At constant brake mean effective pressure, the engine brake thermal

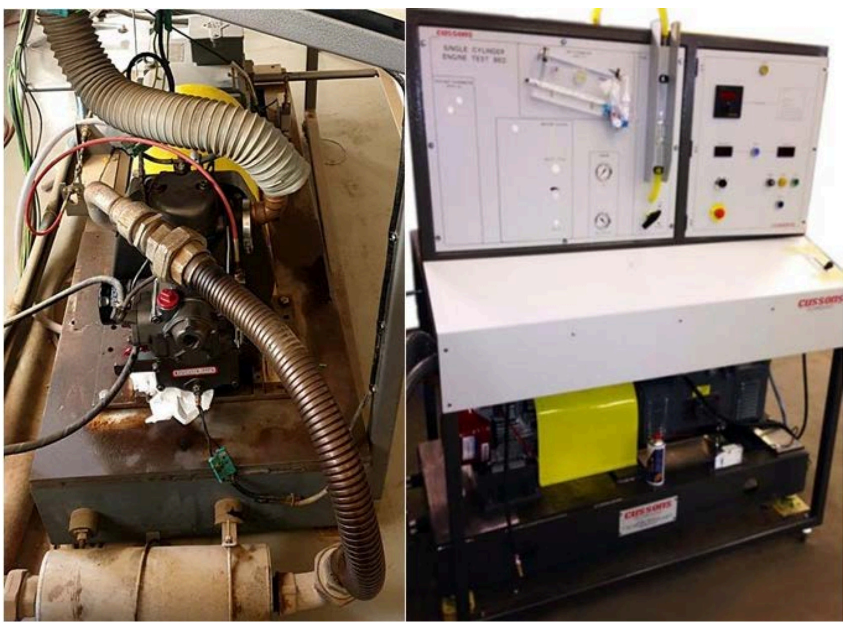

Figure 1. Test-bed with single-cylinder four-stroke spark-ignition engine.

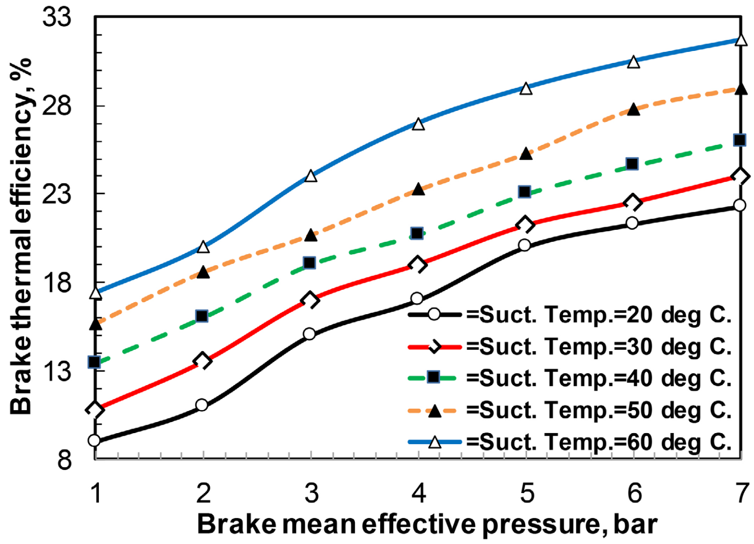

Figure 2. Effect of inlet temperature on the engine efficiency.

efficiency increases with an increase in intake temperature due to an increase of heat addition from increasing the combustion chamber temperature. This means that an increase in the intake temperature leads to an increase in the temperature inside the combustion chamber, which leads to an increase in engine efficiency.

Figure 3 shows the effect of increasing the suction or inlet temperature on the percentage of carbon monoxide (CO) emissions in the exhaust gas from a gasoline engine. Increasing the intake temperature reduces the carbon monoxide in the exhaust, leads to complete combustion, and enhances engine efficiency. Figure 4 shows the effect of engine suction temperature on NOx emissions. The figure shows an increase in the percentage of NOx emissions with increasing the engine intake temperature. The higher air intake temperature leads to decrease oxygen availability resulting in unstable combustion where partial burn and misfire may occur. It also was found that the emissions of CO decreased with the decrease of air intake temperature regardless of engine speed. The increase in the percentage of oxygen at low temperatures led to a complete fuel mixing process and complete combustion. Figure 5 summarizes the results of increasing the inlet temperature of the tested engine intake which changed from 20˚C to 60˚C, in 10˚C increments each time. From the results shown in Figure 5, it is noted that the braking efficiency of the engine increases with the increase in the temperature of the inlet air. The optimum temperature of the air entering the engine (60˚C) was determined with respect to the highest efficiency.

As for the exhaust emissions, they increased with the increase in the temperature of the air entering the engine. This is explained by the fact that heating the air entering the engine leads to the vaporization of the fuel to increase its temperature, and thus increase the engine exhaust emissions. To explain the improvement in engine efficiency with increasing the incoming air, this is due to the increase in the amount of heat generated inside the combustion chamber with its higher temperature result due to heating the incoming air.

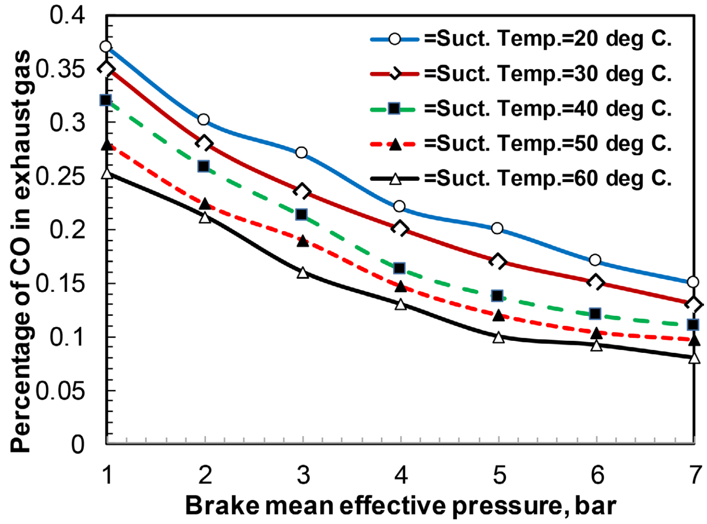

Figure 3. Effect of increasing the intake temperature on the percentage of carbon monoxide emissions.

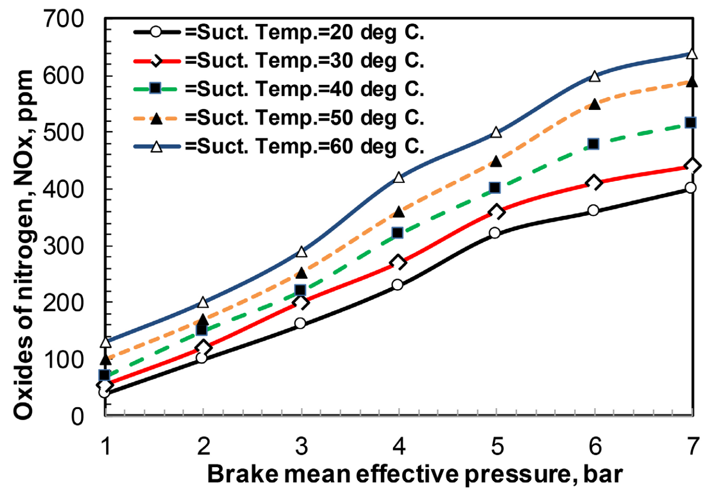

Figure 4. Effect of engine suction temperature on NOx emissions.

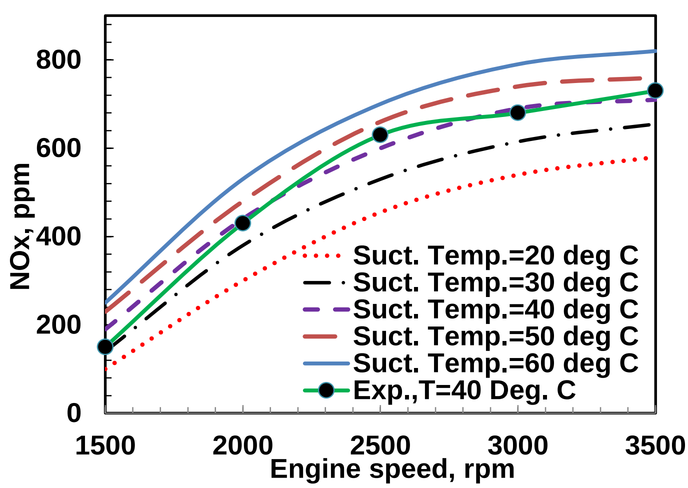

Figure 5. Effect of engine intake temperature on efficiency and NOx emissions.

3. Theoretical Work

3.1. Tested Parameters

There are many factors that affect heat generation and emissions within an engine cylinder. By carefully studying these factors, the most effective factors were selected to study their effect on engine efficiency and pollution rates in the outgoing gases. These factors are the temperature and pressure of the air entering the engine, the equivalence ratio, engine speed, compression ratio, turbulence kinetic energy, combustion chamber design, and volumetric efficiency. The engine has been theoretically tested using two programs, Gaseq and Ansys at different engine intake air temperatures from 20˚C to 60˚C in 5˚C increments. The engine intake pressure was changed from Pi = 1 bar to 1.5 bar in seven steps, with increments of 0.1 bar. The engine was tested at five or six different values of: air-to-fuel ratios of Φ (from 0.8 to 1.2), and speeds (from 1500 rpm to 3500 rpm). Also, three variants of the engine's cylinder heads were tested, which are bowl-in-piston, flat-and hemispherical.

3.2. Computational Analysis

The present computational analysis uses the Gaseq program, the input factors of the intake temperature, intake pressure, and equivalence ratio and the Ansys program (version 15) for the input factors of the shape of the combustion chamber, compression ratios, volumetric efficiency, fuel-air ratios, both to reach the final temperature, pressure, the amount of heat generated from combustion, the percentage of pollution from the exhaust. The inlet valve is selected as a shut-off angle as the decomposition geometry since it is more concerned with simulating the power stroke combustion of the engine cycle from the valve closing to the end of the compression stroke to complete the chosen inlet geometry.

3.2.1. Effect of the Engine Inlet Conditions on Engine NOx, Brake Power, Torque, and Temperature

The effect of changing the intake temperature, pressure, and the equivalence ratios on the combustion temperature, pressure, NOx emissions, and engine brake torque have been studied using the different programs and tested successfully. Figure 6 shows the effect of inlet temperature on the engine exhaust gas emission. The NOx emissions increases with increases in engine speed at constant inlet temperature. This is due to higher temperatures produced by the engine at higher engine speeds. At the same engine speed, the emissions of nitrogen oxides increase with increased engine inlet temperature due to the resultant high combustion temperatures. The effects of increasing engine speeds on NOx emissions at constant entry temperature of the experimental are compared with theoretical and show an acceptable agreement. On the other hand, based on the available experimental or theoretical data, at engine speeds lower than 1500 rpm, there are no significant differences in NOx emissions. Also, such decreases in NOx emissions also result from the lower combustion temperature due to the high oxygen content in the gasoline molecules. Figure 7 shows the effect of the suction

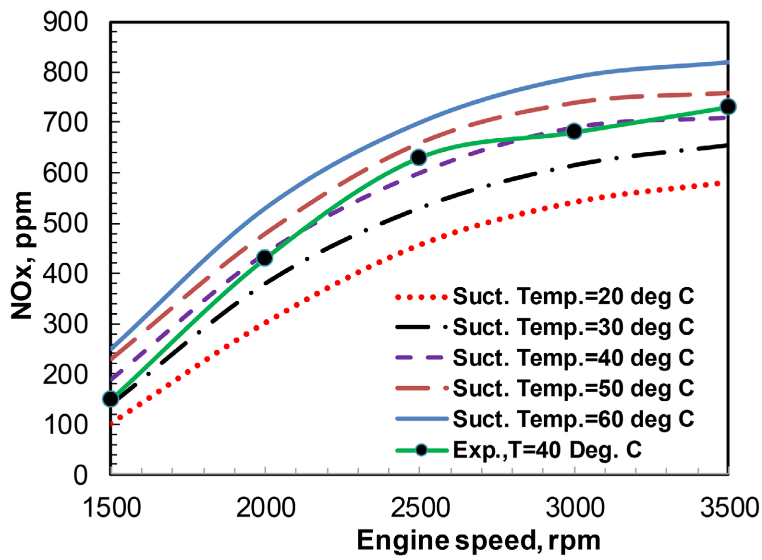

Figure 6. Effect of inlet temperature on the engine exhaust gas NOx emissions.

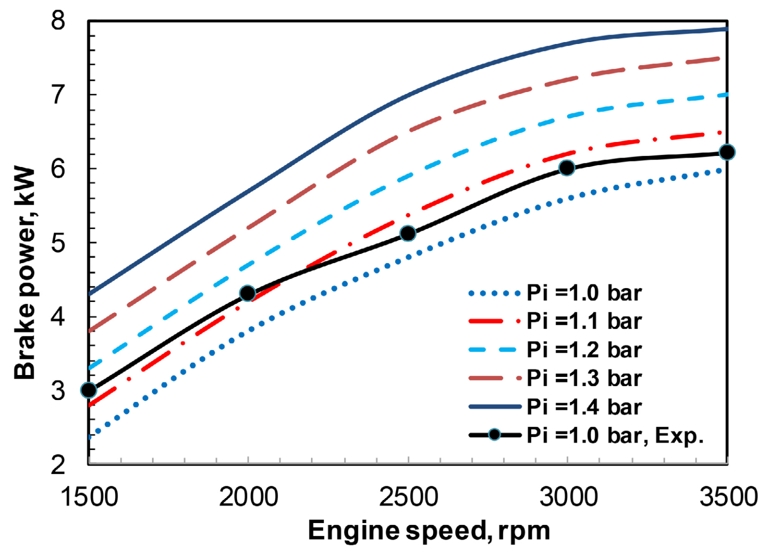

Figure 7. Effect of engine suction pressure of the exhaust gas NOx emissions.

pressure on the brake power at variable engine speeds. It is clear from the figure that the engine brake power increases with increasing intake pressure at all speeds. Because increasing the intake pressure has increased the combustion chamber pressure and this leads to an increase the heat generation and then increases the engine power. It is noted from the figure that the brake power increases with increase in the engine speeds. Experimental data were drawn for the engine at the atmospheric pressure with the theoretical results and showed an acceptable match.

Figure 8 shows the effect of the equivalence ratio on the gasoline engine brake torque and the percentage of emissions in the exhaust gas. The NOx emissions for the five elegant fuels were maximum at an equivalence ratio of about 0.92. At an equivalence ratio, of 0.8, the NOx emissions are very low. At an equivalence

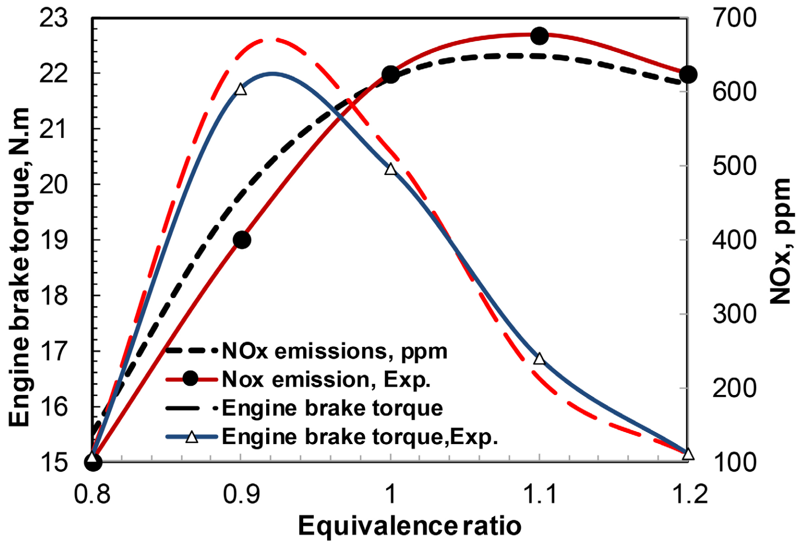

Figure 8. Influence of equivalence ratio on brake torque, and NOx.

ratio of 1.10, the NOx emissions are slightly lower than at $\varphi = 1.20$. The decrease in NOx emissions is attributed to the higher emissions resulting in lower heat release resulting in lower combustion temperature. Comparisons between the theoretical and experimental results were done and show acceptable agreements. It was found that the performance of a gasoline engine with a higher parity ratio or a rich mixture produced slightly lower brake torque. The results of the engine test at the equivalence ratio of 0.92, gives a 35% reduction in emissions with an improvement in brake torque produced by about 10% relative to the engine running in stoichiometric condition. At stoichiometry, the brake torque for both the experimental and theoretical was lower than the lean mixture of equivalence ratio of 0.92 producing 10% less. In the rich region, the brake torque was virtually the same with the lean mixture of less than 0.9. However, it is observed from the experimental work that when the engine is running at the equivalence ratio of 0.80 or in the lean mixture, the engine work is unstable, and there is a fluctuation in the torque measurements significantly. While, when the engine is working at an equivalence ratio of 0.92 produces more brake torque and consumes less fuel.

Figure 9 shows the effect of the equivalence ratio on the NOx emissions of a gasoline engine which shows that the NOx emissions are directly dependent on the excess oxygen in the exhaust gas, which is dependent on the equivalence ratio. This means that when the proportion of fuel in the mixture increases, the excess oxygen consumption decreases, and therefore nitrogen oxide emissions are reduced constantly. Conversely, when the proportion of fuel in the mixture decreases, the consumption of oxygen increases, and then the levels of nitrogen oxides emissions increase. The theoretical results (Figure 9) indicate an exponential increase in the pressure and temperature of the combustion chamber with an increase in the fuel-air equivalent ratio. But the results of the experimental data in the figure show that the combustion chamber pressure increases

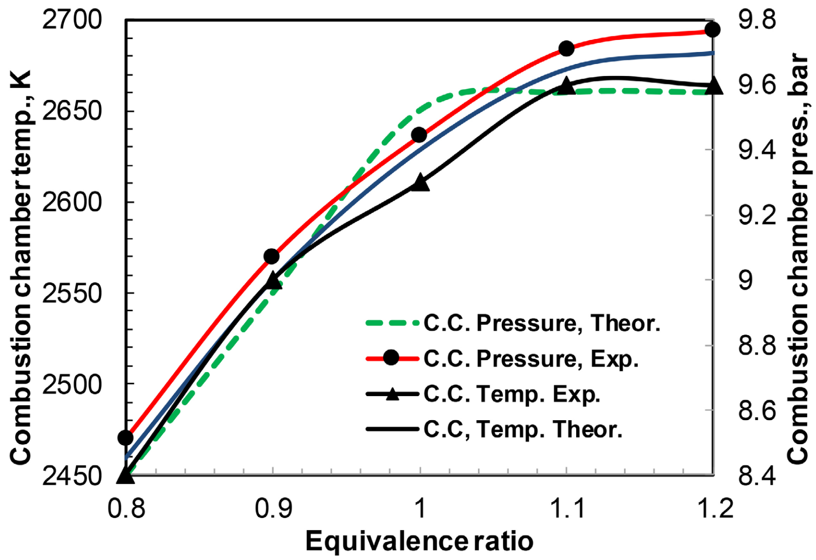

Figure 9. Effect of equivalence ratio on the combustion chamber condition.

with the increase of this equivalent until the stoichiometric value and then does not increase more with the increase in this ratio, but the temperature continues the increasing until this ratio equals 1.1 and then stabilizes. The results that are shown in Figure 9 indicate good agreement with the results represented in Figure 8. These confirm no increase in the engine torque with an increase in the equivalence ratio higher than one but increasing the pollution rates with an increase in the equivalence ratio. It is deduced here from the results of laboratory and theoretical experiments that the work of spark-ignition engines (gasoline engines) at ratios equivalent to higher than one does not improve the braking torque of the engines, but on the contrary, it gives higher pollution rates due to working the engine in the rich mixture or non-complete combustion which leads to more fuel consumption or spend more money.

3.2.2. Effect of Engine Speed on Gas Propagation Velocity

Figure 10 and Figure 11 show the effect of changing the engine speed on the velocity of gas diffusion at different angles in the crank. Figure 10 shows the diffusion velocity contour of the gas mixture inside the combustion chamber at different engine speeds is a harmful diffusion velocity that decreases with the increasing engine speed because the ignition increases linearly with the engine. Figure 10 shows that the highest velocity of the gas mixture propagation velocity inside the combustion chamber occurs at a crank angle of 736˚C and this result is taken from different animation clips (an example of which is represented in Figure 10). It is noticed that when the engine speed increases, the maximum speed of the gas mixture propagation velocity inside the combustion chamber decreases during the combustion period due to the high piston speed. As the flame speed is directly proportional to the turbulence of the mixture, the main factor in increasing the gas mixture propagation velocity and complete combustion. This concluded that increasing the flame speed, which is proportional directly to

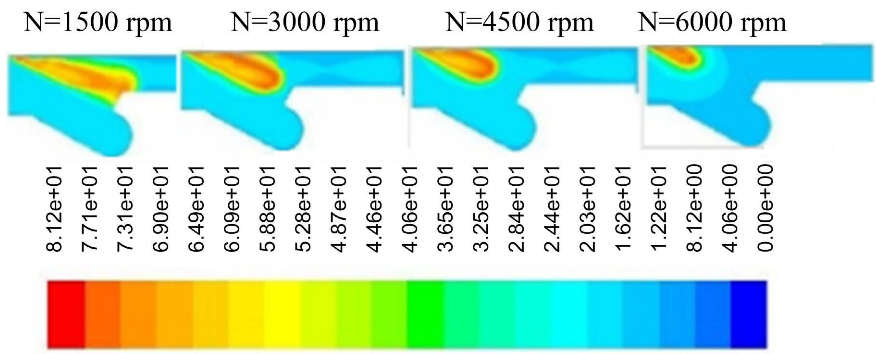

Figure 10. Effect of engine speed on the gas propagation velocity.

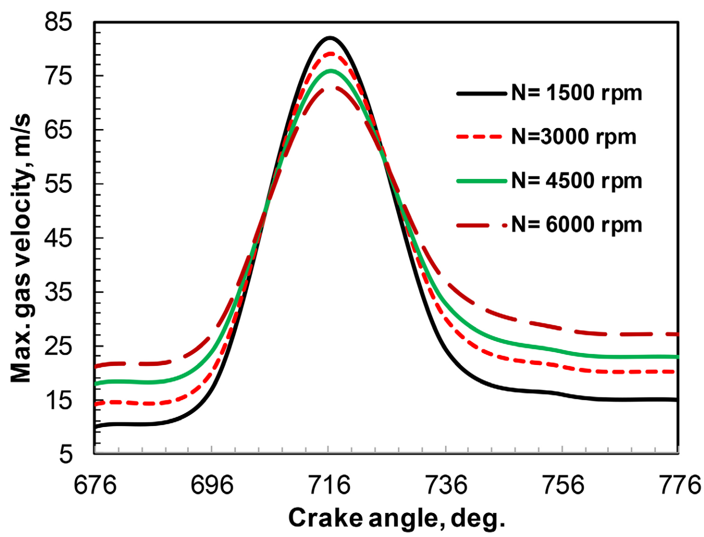

Figure 11. Effect of engine speed on the gas mixture propagation velocity.

the turbulence of the propagation velocity of the gas mixture, plays a very important role in the complete combustion and increases the engine efficiency. But excessive turbulence as a result of increasing the engine speed is not desirable because it increases the combustion quickly and leads to an explosion, also decreases the flame speed by half, and does not pass the combustion chamber.

3.2.3. Effect of Engine Speed on Spray (Particle Traces) Velocity

To study the effect of changing engine speed on spray velocity (particle effects) at different engine speeds 1500 rpm, 3000 rpm, 4500 rpm, and 6000 rpm, respectively. The recorded maximum velocity of the gas mixture inside the combustion chamber of the results from the program used at each crank angle is in Figure 12. It is noted from the figure that the highest velocity occurs at a 728˚ crank angle, and when the engine speed increases, the maximum speed of the spray decreases during the combustion period due to the piston speed being higher than the speed of the flame, and this leads to a reduction in the output power.

3.2.4. Effect of Engine Suction Pressure on the Ignition Potential

Figure 13 shows the significant influence of the pressure around the engine on

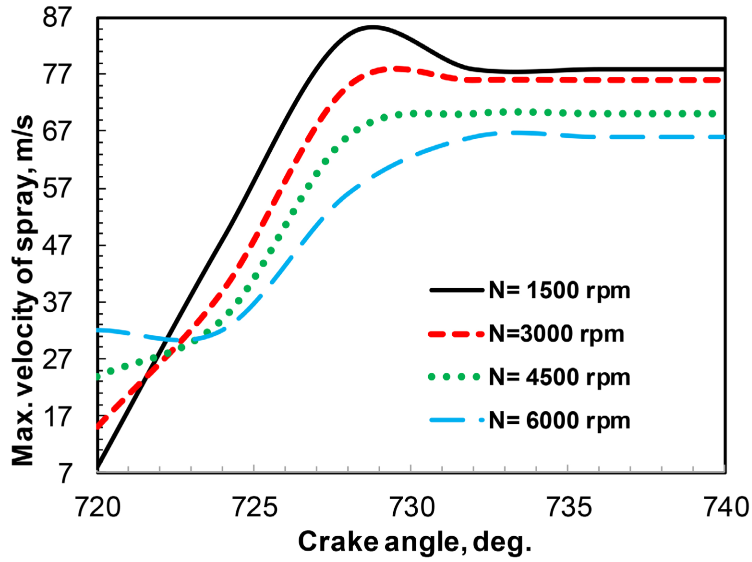

Figure 12. Effect of engine speed on the maximum velocity of spray.

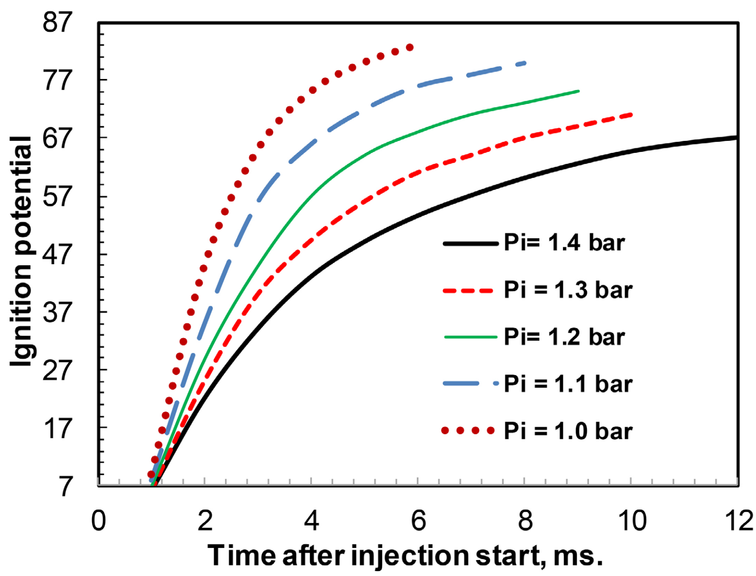

Figure 13. Effect of engine intake pressure on the ignition potential.

the ignition potential. As the ambient pressure increases the time interval with higher ignition potential moves downstream. And as the intake pressure increases the time after injection increases. Because increasing engine inlet pressure increases the pressure inside the combustion chamber leads to an increase in the higher value of the possibility of ignition or achieving ease of ignition, and helps to reduce the suppression of flame beads in addition to increasing the amount of high-density air that helps to form the flammable mixture.

4. Conclusions

Two different programs (Gaseq and Ansys) were used to find the effect of combustion chamber shape, compression ratios, ambient conditions, heat generation, gasoline engine performance. The result indicated that increasing the intake temperature leads to increases in all heat generation, the overall engine efficiency, ratios of CO_2, and NOx emissions. Increasing the intake pressure leads to increases in the exhaust temperature, exhaust pressure, and carbon dioxide, and conversely, it has a positive effect on carbon dioxide and nitrogen oxide. Theoretical and laboratory results showed an increase in the pressure and temperature of the combustion chamber by increasing the ratio of fuel to equivalent air up to the stoichiometric value and then fixing after this ratio. Do not increase the torque of the sand engine with an increase of the parity ratio greater than one, but rather lead to an increase in pollution rates. Therefore, it is recommended not to run gasoline engines with equilibrium ratios higher than one, because they improve the braking torque and even increase pollution rates as a result of operating the engine in conditions of incomplete combustion, which leads to increased fuel consumption. And more money wasted. Increasing the engine speed causes the piston to speed up, which reduces the spray velocity relative to the flame speed during the combustion process, and leads to a decrease in the relative power the engine produces. The high compression ratio in the piston provides good combustion but leads to combustion knocks.

The work of spark-ignition engines at ratios equivalent to higher than one does not improve the braking torque of the engines, but on the contrary, it gives higher pollution rates due to working the engine in the rich mixture or non-complete combustion which leads to more fuel consumption or spend more money. Increasing the flame speed, which is proportional directly to the turbulence of the propagation velocity of the gas mixture, plays a very important role in the complete combustion and increases the engine efficiency. When the engine speed increases, the maximum speed of the spray decreases during the combustion period due to the piston speed being higher than the speed of the flame, and this leads to a reduction in the output power. As the ambient pressure increases the time interval with higher ignition potential moves downstream.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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