Effect of Methane Percentage in Natural Gas Fuels on Spark Ignition Engine Performance

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Abstract

Research nowadays has become interested in how to improve alternative fuels to reciprocating internal combustion engines, as it has become necessary due to the high prices of conventional fuels, and also its significant contribution to hazardous pollutants. Natural gas is one of the most promising fuel alternatives for the future, which will help reduce harmful emissions. In this paper, a computational simulation software model of a four-cylinder, 5000rpm natural gas spark ignition engine is developed. The computational program works on the thermodynamic fundamentals of the gaseous cycles of reciprocating internal combustion engines. The effect of different proportions of methane gas in the natural gas mixture on the performance of the engine was studied, where the pressure, temperature and quantities of nitrogen oxide formation inside the cylinder were calculated as a function of crank shaft angle of the engine. The indicated mean effective pressure, indicated power, thermal efficiency, maximum pressure, maximum temperature, amount of nitrogen oxide formation and indicated specific fuel consumption were also calculated at different equivalence ratios of fuel and air, and also at methane gas containment ratios in natural gas fuels. The results showed that the equivalence ratio and methane percentage in the fuel have a strong effect on engine performance. The high percentage of methane presence caused a decrease in the thermal efficiency of the engine, which harmed a decrease in the indicated power of the engine. On the other hand, natural gas contains large proportions of methane gas, causing a decrease in the amounts of nitrogen oxide formation, as well as a decrease in the indicated specific fuel consumption. It has been proven that the proportion of methane gas in natural gas fuels improves combustion, emission and performance, when added by a high percentage, natural gas is usually generally composed of methane (85-96%) and can be used in both reciprocating internal combustion engines as an alternative to gasoline and diesel fuels.

Keyword. SI engine; Natural gas; Equivalence ratio, NOx emissions; fuel consumption

Introduction

Alternative fuels such as hydrogen, acetylene, natural gas, ethanol and bio-fuels are used in internal combustion engines. It is known that hydrogen gas in its gaseous state is about 14 times lighter than air. In addition, it is the cleanest fuel in the world. On the other hand, need low minimum ignition energy to start the combustion process, and also it is possible to operate the engine with a very low air-to-fuel ratio (very lean mixture), so it needs a special design for the combustion chamber with spark ignition engines. Hydrogen fuel has been shown to have a significant role in improving combustion, product emissions and engine performance, when added by 20% to the fuel. Natural gas is generally composed of methane (85-96%) and can be used in both gasoline and diesel engines. Hydrogen has been shown to improve combustion, emissions and performance, when added by 20% to fuel. Natural gas is generally composed of methane (85-96%) and can be used in both gasoline and diesel engines. Ilhak. et. al (2019) [1] studied the effect of adding ratios of a different fuel group, testing the effects of natural gas with hydrogen, natural gas + hydrogen (HCNG), ethanol, ethanol + gasoline, ethanol + hydrogen, acetylene and acetylene + gasoline mixtures on engine performance and emissions. The results were that each fuel has positive and negative properties for use in internal combustion engines. There are differences in the effects of each alternative fuel on emissions and engine performance. Future studies must be carried out to obtain suitable hybrid fuels by comparing these types of alternative fuels to reduce all emissions and improve engine performance.

Natural gas fuels are a mixture of hydrocarbon compounds, usually extracted from the ground at great depths, which are stored in rock reservoirs. One of the most important components of this natural gas is methane (CH_4)with different ratios of other hydrocarbon gases including ethane (C_2H_6), propane (C_3H_8), and butane (C_4H_{10}). Natural gas is widely used in the field of transportation and industrial applications. It has become one of the dominant energy used in various fields, including heating systems and heat engines in electric power plants and also by reciprocating internal combustion engines as an alternative to fossil liquid fuels such as diesel and gasoline, where it is considered one of the cleanest burning fossil fuels where it primarily produces carbon dioxide, water vapor and small amounts of nitrogen oxides. Where the demand for it has increased significantly nowadays due to the efficiency of combustion processes in the chambers of heat engines, and its polluting emissions have decreased compared to liquid fossil fuels, and also it is characterized by the ease of mixing it with air, which makes it characterized by the property of minimum lower limit of combustion of the mixture air and fuel, Which gives the possibility of operating heat engines with a very lean mixture. Natural gas is considered an attractive fuel for many reasons. It is cheaper fuel than liquid fuels such as gasoline or diesel, it has inherently lower air pollution emissions, it has less greenhouse gas emissions, available in large quantities of the world's oil reservoirs, but also not without some of the main problems that must be solved when using natural gas engines, so the lack of clarity of the preference for compromise between emissions and fuel economy, as well as the optimal air-to-fuel ratio changes with both operating conditions and fuel properties[2]. In this paper the equivalence air to fuel ratio are studied from very lean mixture to the ratio of stoichiometric equivalence ratio.

Many researches have been interested in using this type of alternative fuel in obtaining thermal energy. In this paper, one of its important applications in heat engines will be emphasized, specifically with reciprocating spark ignition engines. Since natural gas fuels contain a high content of CH_4 (methane) which is usually about 90% of total NG, emphasis will be placed on the impact of the proportion of methane gas on the performance of spark ignition engines. Methane gas with its chemical composition It contains a small percentage of carbon, that is, it contains one atom of carbon with 4 atoms of hydrogen causing a significant decrease in the formation of CO_2 in combustion products compared to conventional fuels gasoline, where it reaches a decrease of 30% [3], and this decrease contributes to reducing the impact of global warming. Therefore, this fuel should be approached and used as an alternative fuel with reciprocating spark ignition engines. This paper will study the effect of the percentage of natural gas containing methane on engine performance; such as a thermal efficiency, indicated power, the amount of nitrogen oxide pollutant emission and also the specific fuel consumption. Although the brake power of a natural gas-fueled engine is 16% lower compared to gasoline engines [4], there is a significant improvement in engine performance, for example the specific brake fuel consumption of the natural gas engine is always lower which causes an improvement in thermal efficiency by up to 12% [4,5,6]. As for the dangerous toxic pollutant NOx gas resulting from combustion processes, which in its formation depends on high temperatures during the combustion process, which contributed natural gas when used by spark ignition engines to decrease NOx to about 68% when operating the engine from the partial load of 90% to the full load compared to gasoline engines. Compressed natural gas (CNG) improves brake specific fuel consumption (BSFC) and thermal efficiency which has a direct impact in CO_2 reduction. From the results of previous studies on engines modified with CNG regardless of the combination of CNG with other fuels or using pure compressed natural gas, it will probably have its best if a dedicated CNG engine will be created (combustion chamber, compression ratio) and fully optimised (spark advance, fuel injected mass)[7].

Results and Discussions

The effect of the percentage of natural gas fuel components on the performance of a spark ignition engine naturally air aspirated at atmospheric pressure of 1 bar and temperature 300 K on the performance of the engine, in terms of indicated power, specific fuel consumption and NOx emissions. In this study the methane compound percentage in a natural gas mixture was the basis, and the equivalence ratios of this mixture of natural gas with air are different, In this paper, the equivalence ratio from $\emptyset = 0.6$ (very lean mixture) to $\emptyset = 1.0$ (Stoichiometric mixture) have been selected. Seven different percentage of the natural gas mixture composition were selected as summarized in Table 1. Also in this table the air ratio was calculated with the different proportions of the components of the stoichiometric natural gas to air mixture.

Table 1. Seven different percentage of the natural gas mixture composition.

CH_4	100%	90%	80%	70%	60%	50%	0%
C_2H_6	0%	7%	14%	21%	28%	35%	70%
C_3H_8	0%	2%	0.04	6%	8%	10%	20%
C_4H_{10}	0%	1%	0.02	3%	4%	5%	10%
(A/F) st	17.2	16.934	16.72	16.543	16.394	16.268	13.371

The running simulation result is all engine performance data with the proportions of natural gas components (Methane, Ethane, Propane and Butane), and also with the different equivalence ratios of a four-stroke engine at a speed of 5000 rpm, and a compression ratio of 8.6. This model works on the basis of thermodynamic relationships with gas cycles of spark ignition engines, [8,9]. In this paper, the simulation result of engine performance is thermal efficiency, indicated power, indicated specific fuel consumption, NOx pollutant formation rate as well as temperature and pressure in the cylinder.

It is known that equivalence ratio is the key to the design of any fossil fuel heat engine, as it has a direct impact on the performance of the engine. The equivalence ratio mode is the most commonly used mode for engine simulation, especially in equivalence ratios for the very lean mixture, where thermal efficiency increases and the amounts of NOx pollutants are minimized.

In this paper the engine was selected from the paper [10], Table 2 shows the specifications of this engine, and specifications are used as input data for the simulation program.

Table 2. Engine specifications

Engine type	Four stroke, Spark ignition
Induction	Naturally aspirated
Number of cylinders	4 cylinder- In line
Bore (mm)	86
Stroke (mm)	86
Connecting rod length (mm)	153
Displacement volume (cm3)	1998
Compression ratio	8.6
Half stroke to rod ratio	0.28
Engine speed (rpm)	5000
Burning angle (θ_b) [Deg]	60
Start of ignition (θ_s) [Deg]	30 BTDC
Initial pressure (Pi) [Bar]	1
Initial temperature (Ti) [K]	300
Wall temperature (Tw) [K]	420

The overall engine work can be determined by integrating the area under the crankshaft angle and pressure (P-θ) diagram as shown in Figure 1, or the crankshaft angle with the temperature (T-θ) diagram inside the cylinder, as shown in Figure 2. A lot of previous work involved mainly predicts the pressure and temperature inside the combustion chamber. From figure 1 and 2, show that the effect of the presence of methane gas in the natural gas mixture is noticeable, ;the higher the proportion of methane in the natural gas mixture, the lower the pressure and temperature of the gases inside the cylinder.

Also the diagram of the pressure and temperature of the gases inside the cylinder as a function of the crank shaft angle of the spark ignition engine works at a full load at 5000 rpm, showing the maximum pressure of the gases inside the cylinder is 57.1 bar at the proportion of methane 0% and the maximum pressure drops to 55.9 bar at the proportion of methane gas 70%, and the lowest is at the percentage of methane 100% where the maximum pressure was 55.3 bar. The same behavior for the average temperature of the gases inside the cylinder, where the maximum temperature was 2374.7 K at the percentage of methane 0%, and decreased to 2350.9 K when the proportion of methane gas in the natural gas mixture was 70%.

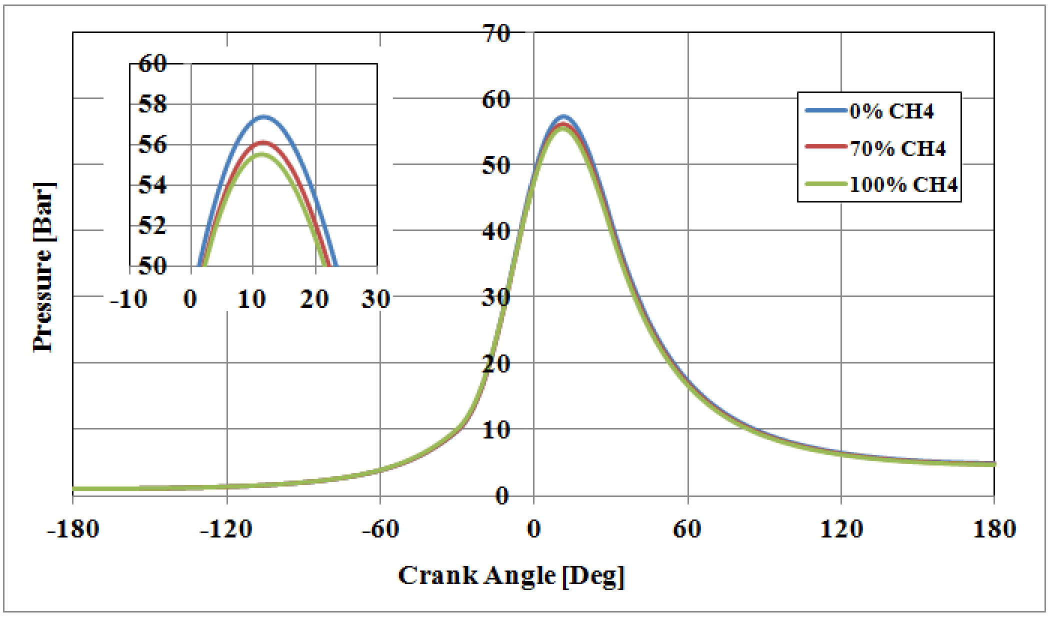

Figure 1 crank shaft angle and pressure in the cylinder at different percentage of CH_4 and equivalence ratio (ϕ = 0.8)

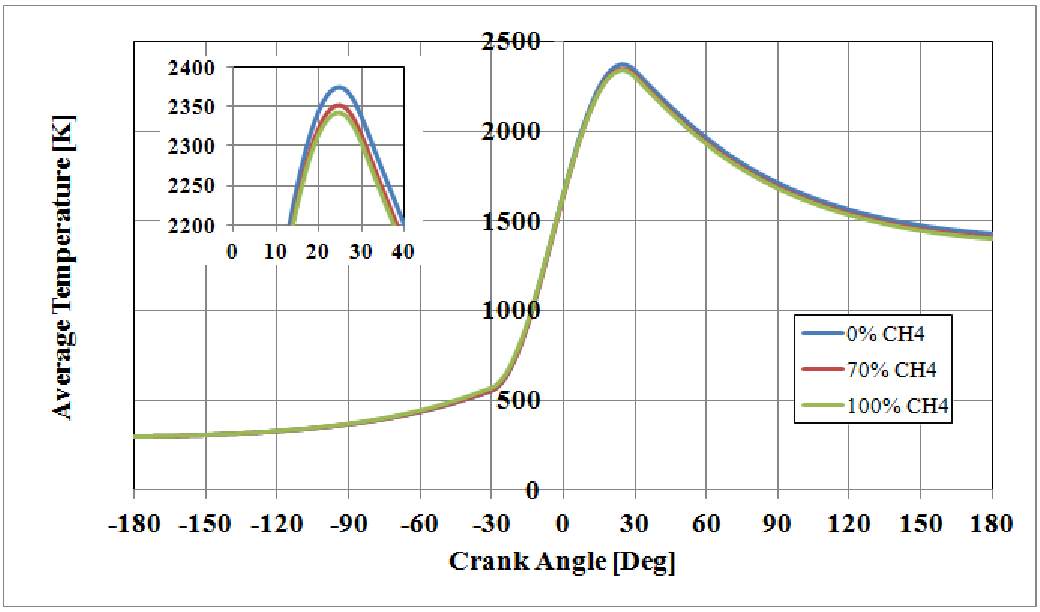

Figure 2 crank shaft angle and gas average temperature in the cylinder at different percentage of CH_4 and equivalence ratio (ϕ = 0.8)

The maximum temperature dropped further when the fuel was entirely methane gas reaching 2333.3 K. This drop in temperature directly affects the formation of nitrogen oxide gas, as shown in Figure 3. From the figure it is shown that the maximum amount of nitrogen oxide gas was when the proportion of methane 0%, where the amount of methane gas formed in one cycle was 2269 PPM, while the amount of nitrogen oxide decreased to 1749PPM when the proportion of methane in the natural gas mixture 70%. It fell further to 1595PPM when the fuel was entirely methane.

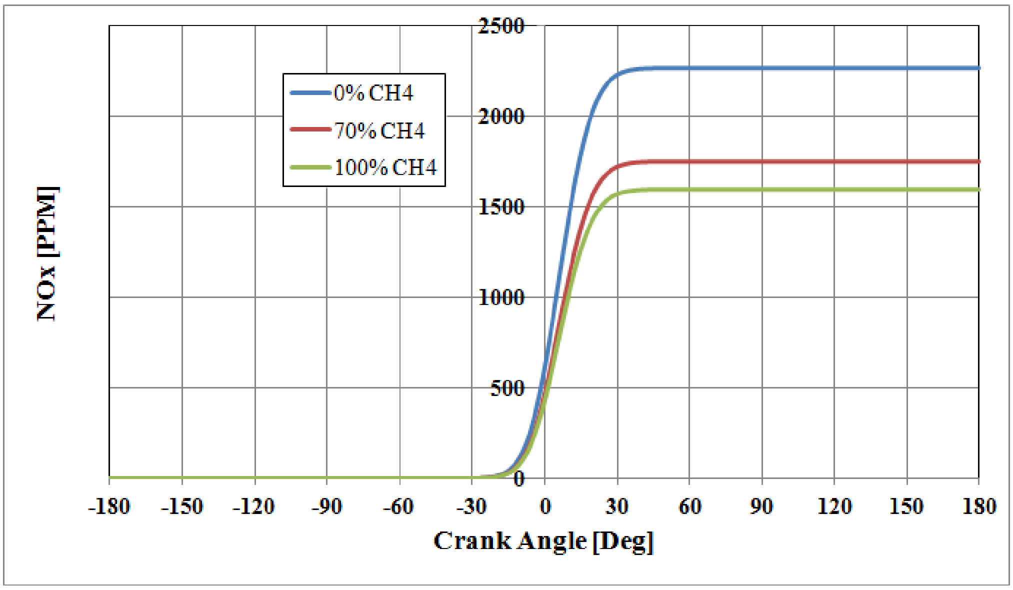

Figure 3. crank shaft angle and NOx formation in the cylinder at different percentage of CH_4 and equivalence ratio (ϕ = 0.8)

The NG spark ignition engine has been tested over an air-to-fuel equivalence ratio of 0.6 to 1.0 at various composition of natural gas components. Methane is the always dominant component of natural gas is the first member of alkane's family. Since it has a high H/C ratio, natural gas is known as the cleanest fuel in fossil fuels. The tests were performed at full load at engine speed of 5000 rpm. Various data were calculated on engine performance, such as maximum pressures (Pmax), maximum temperatures (Tmax), imep, indicated power (Pi), thermal efficiency (ηth), indicated specific fuel consumption (ISFC), and nitrogen oxide (NOx) emissions. Figure 4. Shows the maximum pressure (Pmax) of the gases in the cylinder during one cycle as a function of equivalence ratio at different percentage of CH_4 in the natural gas fuel mixture. As can be seen in Figure 4, the Methane adding causes a decrease in maximum pressure and maximum pressure were calculated when the percentage of methane in the natural gas is 0%. The same trend for the maximum temperature of the gases in the cylinder, Figure 5 Shows the maximum temperature (Tmax) of the gases in the cylinder during one cycle as a function of equivalence ratio at different percentage of CH_4 in the natural gas fuel mixture. The highest maximum temperature was calculated at percentage of methane of 0% and decreases to the lowest maximum temperature when the percentage of the methane is 100%. Equivalence ratio has a strongly effect on the maximum pressure and temperature. From figures 4 and 5, at very lean mixture (ϕ=0.6) the maximum pressure and temperature are lower values than for equivalence ratio at stoichiometric ratio (ϕ=1), the results show that Pmax. and Tmax. are increased with percentage of 25% and 27.5% respectively.

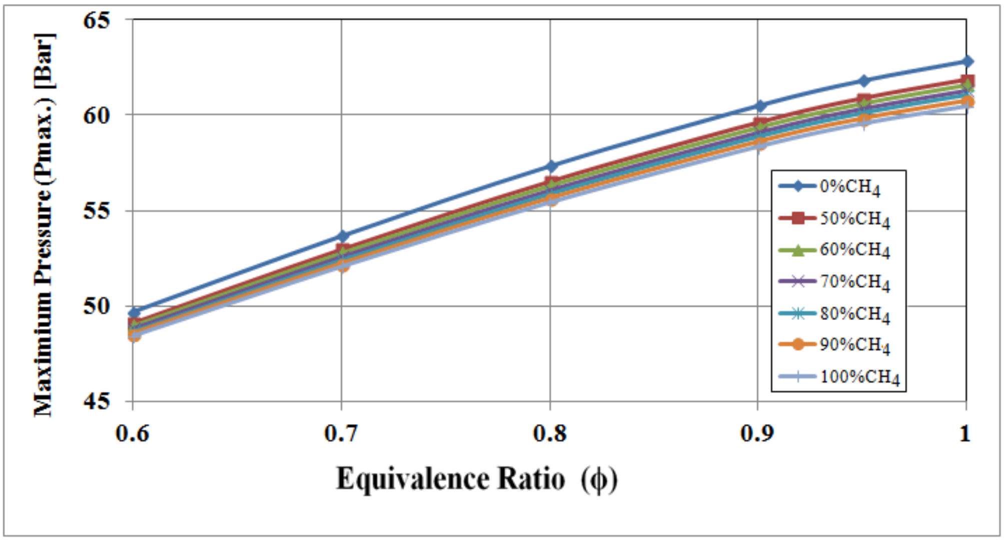

Figure 4. Maximum pressure of gases in the cylinder as a function of equivalence ratio.

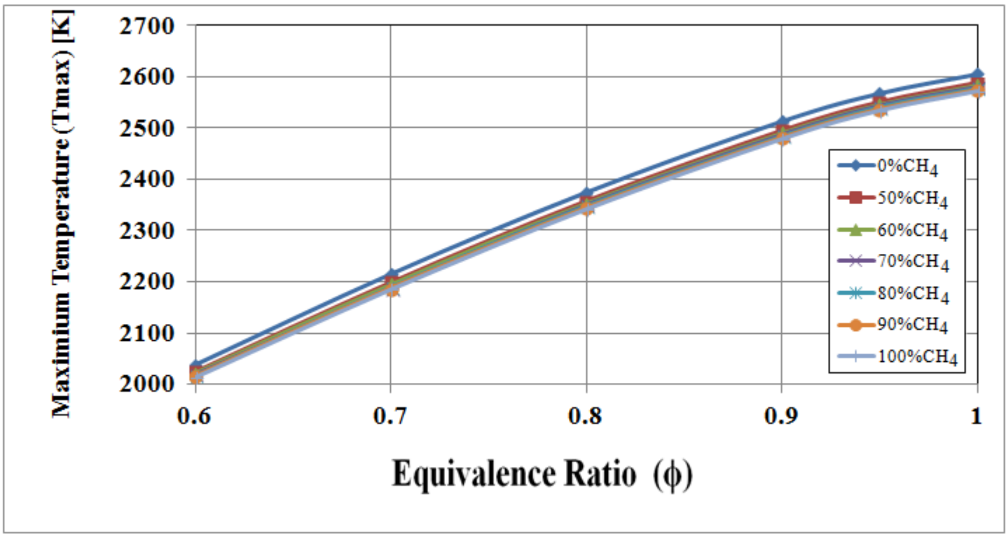

Figure 5. Maximum temperature of gases in the cylinder as a function of equivalence ratio.

Figure 6. shows the indicated mean effective pressure (imep) as a function of equivalence ratio at different percentage of CH_4 in the natural gas fuel mixture. The engine's indicated power is known to be proportional to the indicated mean effective pressure, and the indicated mean effective pressure of the engine depends strongly on the equivalence ratio. Figure 7 shows the indicated power as a function of equivalence ratio. At stoichiometric equivalence ratio induced higher indicated mean effective pressure, and the lower values of imep at very lean mixture. imep increased with a percentage of 28% for all methane percentage in natural gas fuel mixture.

Her the effect of CH4 percentage are also effect on the imep, maximum values are calculated at 0% of CH4. That because the effects of stoichiometeric ratio of air to fuel, for methane fuel (100%CH_4) less air needed for stoichiometric ratio {$(A/F)_{st}$=17.2$\left[\frac{kg\ of\ Air}{kg\ of\ fuel}\right]$} compared natural gas fuel without Methane (0% CH4) need more amount of air to reaches the stoichiometric ratio {$(A/F)_{st}$=13.371 $\left[\frac{kg\ of\ Air}{kg\ of\ fuel}\right]$}, results show that at the stoichiometric ratio imep = 13.5bar for 100% CH_4, and imep = 14.5bar for 0%CH_4. Also the results of indicated power for four cylinder in Figure 7 shows that the Methane percentage has significantly effected on the indicated power, at stoichiometric ratio the indicated power (Pi) for 100% CH_4 is 112.8 kW, and for 0% CH_4 is 120.8kW.

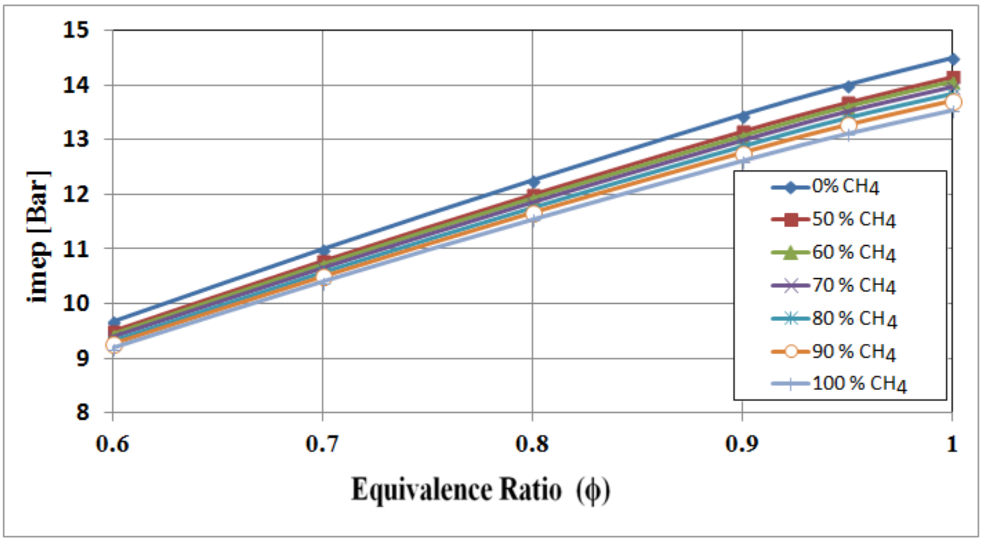

Figure 6.Indicated mean effective pressure (imep) as a function of equivalence ratio at different percentage of CH_4 in the natural gas fuel mixture.

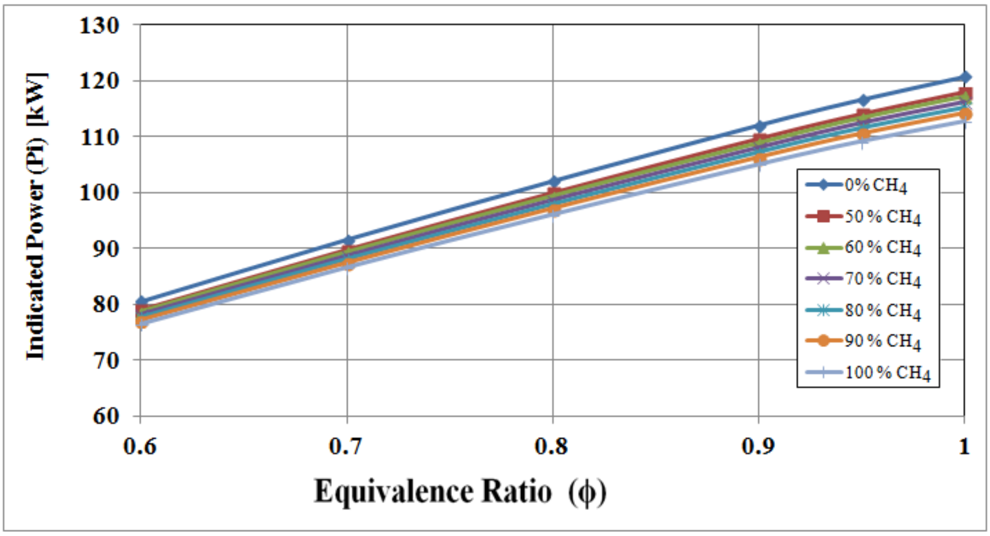

Figure 7.Indicated power (Pi) as a function of equivalence ratio at different percentage of CH_4 in the natural gas fuel mixture.

To evaluate any heat engine; thermal efficiency is an indicator of its performance. It demonstrates how much thermal energy generated from burning of fuel inside the combustion chamber is converted into the work done by the engine. From Figure 8 thermal efficiency is strongly affected by the equivalence ratio. The results showed that the thermal efficiency increased from 40.2% at the stoichiometric equivalence ratio to 44% at the very lean mixture ($\phi = 0.6$) at 0% methane. Also the percentage of methane gas presence in natural gas fuels has an impact on the thermal efficiency of the engine. The higher the proportion of methane gas in the natural gas mixture, the lower the thermal efficiency.

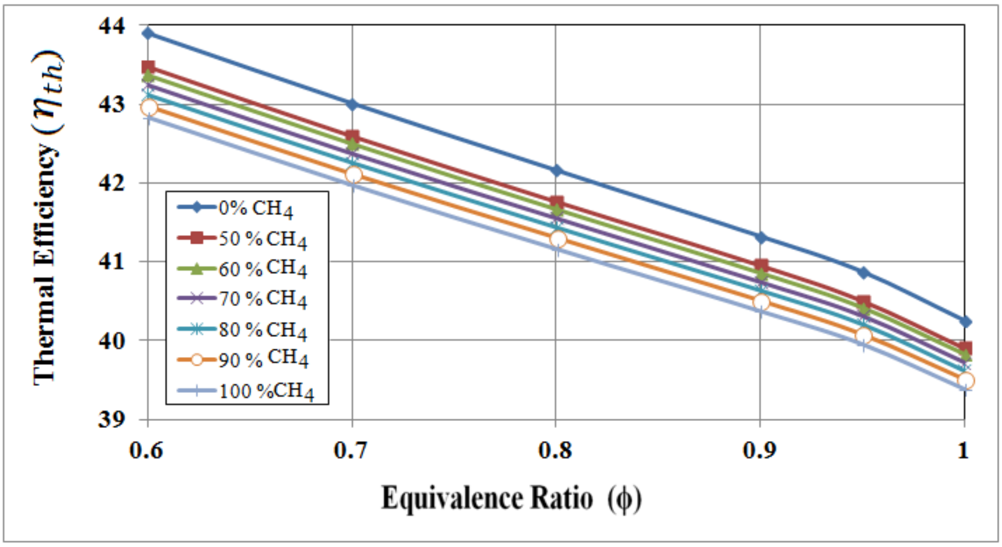

Figure 8. Thermal efficiency (η_{th}) as a function of equivalence ratio at different percentage of CH_4 in the natural gas fuel mixture.

Reciprocating internal combustion engines are one of the heat engines as a source of emission of polluting nitrogen oxide to the environment, as it depends in its formation on the high temperature of combustion gases, the higher combustion temperature, the produce high amount of its formation, and also depends in its formation on the speed of combustion process inside the engine cylinder, at low combustion process speed will induce the high formation of nitrogen oxide. That means; high speed of the engine, the lower the formation of nitrogen oxide will decrease. In this paper the engine speed is fixed at 5000rpm. This study was concerned with the effect of both the proportion of methane gas in the natural gas fuel mixture and also the equivalence ratio of the fuel mixture with the air. Figure 9 shows the amount of nitrogen oxide formation as a function of equivalence ratio and at different proportions of methane gas in natural gas fuel. The result in Figure 9 showed that the equivalence ratio has a strong effect on the formation of nitrogen oxide. At closer to the soichiometric ratio of the mixture the high amount of nitrogen oxide formation, there is a small decrease at the soichiometric ratio even though the high temperature, but in this case the combustion speed plays a role in this slight decrease, as a result of the high speed of the flame which does not give a chance of nitrogen oxide formation in a larger amount. The results also showed that the amount of nitrogen oxide formation is affected due to the different proportions of natural gas containing methane gas, the higher the percentage of methane in natural gas the less the amount of nitrogen oxide formation. For example, at the stoichiometric equivalent ratio, the amount of nitrogen oxide was when natural gas contained 100% methane gas and 0% methane gas is decreased by 15%.

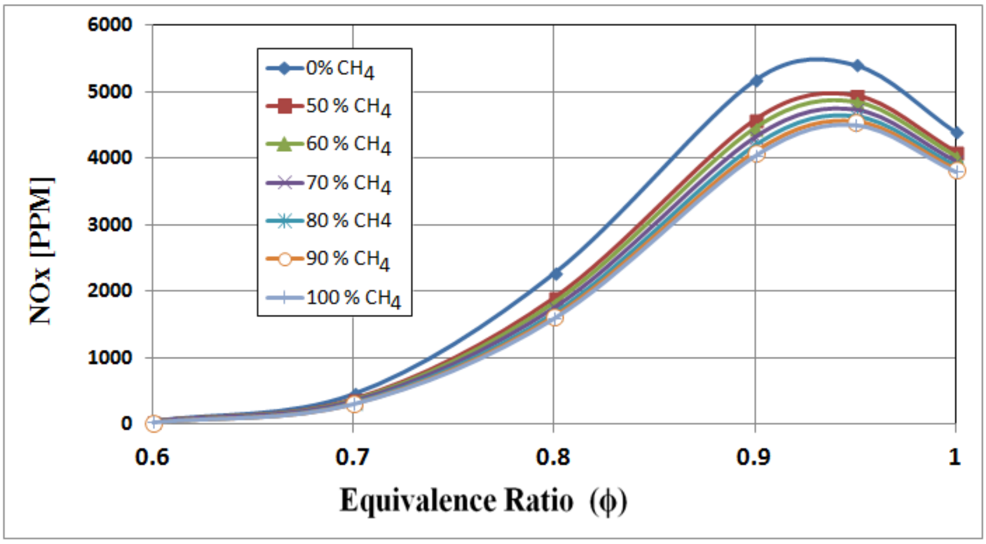

Figure 9. NOx formation as a function of equivalence ratio at different percentage of CH_4 in the natural gas fuel mixture.

Figure 10 illustrates the effect of equivalence and methane percentage in natural gas on the indicated specific fuel consumption (ISFC) of a four-cylinder four-stroke SI engine. From the figure, it is clear to us that the equivalence ratio has an effect on the specific fuel consumption. As the equivalence ratio approached to stoichiometric ratio, the specific fuel consumption increased, which is normal for the mixture to be richer than the very lean mixture at the low equivalence ratio (ϕ=0.6). Figure 10 also shows that the lower the percentage of natural gas containing methane, the higher the specific fuel consumption.

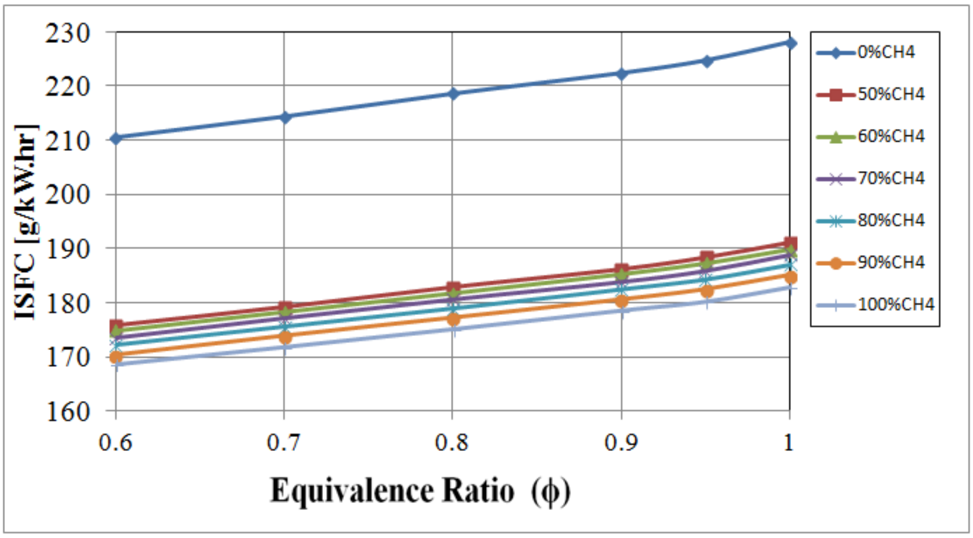

Figure 10. Indicated specific fuel consumption (ISFC) as a function of equivalence ratio at different percentage of CH_4 in the natural gas fuel mixture.

Conclusions

The theoretical analysis has been carried out using simulation model. The simulation investigation of NG with different CH_4 percentage fuel used for high speed SI engine with speed of 5000rpm. The investigation result is shown that the CH4 percentage in NG is playing a significant role on engine performance and engine emissions of NOx. There are several main things to consider when using natural gas engines, the most important of which is the equivalence ratio and also the percentage of natural gas fuel containing methane, in order to improve the rates of decrease in nitrogen oxide secretions and from an economic point of view to reduce the specific fuel consumption. In this study; The highest maximum computational temperature, pressure and NOx formation in cylinder for NG engine are 2605K , 62.8bar and 5399PPM respectively at stoichiometric ratio and CH_4 percentage of 0%, and lowest maximum computational temperature, pressure and NOx formation in cylinder for NG engine are 2571K , 60.4bar and 3801PPM respectively at stoichiometric ratio and CH_4 percentage of 100%. The highest computational thermal efficiency of the engine is 44% at equivalence ratio of 0.6 and CH_4 percentage of 0%, and lowest thermal efficiency of the engine is 42% and CH_4 percentage of 100%. The highest computational indicated specific fuel consumption of the engine is 228 [g/kW.h] at stoichiometric ratio and CH_4 percentage of 0%, and lowest indicated specific fuel consumption of the engine is 182 [g/kW.h] at stoichiometric ratio and CH_4 percentage of 100%.

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