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COMBUSTION AND EMISSION ANALYSIS OF VARIOUS GASEOUS FUELS IN SPARK IGNITION ENGINE USING MATLAB SIMULATION

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ABSTRACT

In this research Hydrogen, Syngas and Compressed natural gas were used to simulate a spark-ignition engine using MATLAB and Simulink. Here, the combustion and emission of the engine using hydrogen, syngas (mixture of carbon monoxide (CO) and hydrogen (H2)) and compressed natural gas were analyzed considering various engine parameters and compared the obtained results with gasoline. The simulation's results were used to describe the physical processes in the combustion chamber, which determine engine power and emission under various operating situations. The performance of each fuel in a spark ignition engine under the same operating conditions, such as equivalency ratio, rpm, compression ratio, and spark timing were compared. The obtained results showed that the hydrogen and syngas can be run in both lean and rich condition, which helps to reduce fuel consumption, whereas gasoline and natural gas can run only at a stoichiometric air-fuel ratio.

Keywords: Spark Ignition Engine, Syngas, Hydrogen gas, Natural gas, Gasoline, Cylinder Peak Pressure, Nitrogen oxide

1. Introduction

Excessive consumption of fossils fuels has been today's generation biggest problem, and it needs to be sort out soon. For this, alternative fuel sources and energy are a thrust for researchers. The massive increase in the world population, the rapid growth in technological development and the standard of living in developed countries over the last decade have created a problematic situation in the area of energy supply [1]. In today's energy scenario, energy demand is steadily increasing. Internal Combustion (IC) engines need new alternative energy sources like hydrogen, syngas or natural gas. The rise in oil prices and environmental pollution encourage the development of competitive alternative energy sources. As a result of numerous studies that have been conducted and are still being conducted, it has been determined that hydrogen can be a superior alternative fuel because it is readily available and even helps reduce pollution [2].

Hydrogen, Syngas, Biogas, Natural gas and liquified petroleum gas (LPG) are promising alternatives to conventional gaseous fuels for spark ignition engines [3]. Each of them is advantageous in its own way and is appropriate for particular uses. The commonly available petroleum-based fuels are natural gas and LPG. Syngas, hydrogen gas, and biogas are renewable forms of fuel energy in a gaseous state. In addition to stationary power generation, CNG is extensively used in the industrial sector. In rural areas without significant infrastructure for the provision of electricity and petroleum goods, syngas can be utilized for transportation, stand-alone power generation, and irrigation [4].

Among the various energy sources, syngas also offers a promising alternative gaseous fuel in place of fossil diesel. Syngas are composed of two diatomic molecules, carbon monoxide (CO) and hydrogen (H_2), which are the buildings blocks upon which entire field fuel science and technology is based on [5]. The major component of syngas is H_2, which has very clean burning characteristics, high flame propagation speed and wide flammability limits. Thus, increased H2 content in a gaseous fuel reduces the combustion duration and thereby increases internal combustion (IC) engine efficiency. It is of great interest that adding H_2 to a gaseous fuel extends the lean limit of gas operation without entering the lean misfire region [6]. Lean mixture combustion has great potential for attaining higher thermal efficiency and low nitrogen oxide (NOx) emission levels with only an insignificant increase in hydrocarbon emissions [7].

In order to diminish vehicular exhaust emissions from fossil fuel, in comparison to other renewable sources, hydrogen is becoming the most promising choice fuel source [8], [9], [10]. Along with biofuels and electric cars, hydrogen is one of three critical low-carbon transportation choices such as, electrical vehicles (EVs). Hydrogen not only avoids the adverse effects of biofuels on land usage and air pollution, but it also has the highest specific energy content compared to fossil fuels [9], [11]. Hydrogen automobiles have been shown to have a threefold lower potential for global warming than other alternative technologies [12], [13]. As a result, renewable resources, particularly hydrogen energy, are the most promising choices for meeting energy demands. Hydrogen mainly found in plant materials, which is a non-metallic, nontoxic fuel that can store 2.6 times more energy per unit mass [14]. However, due to the a very low density, it requires approximately four times more volume for storage when stored as a liquid, and approximately 19 times more volume when stored as a gas [15]. Even though, there are several challenges in the hydrogen production, storage and utilization process, there are limitless benefits to using hydrogen instead of fossils fuels. Therefore, researcher have focused on investigating the applications of hydrogen as a fuel.

Compressed Natural Gas (CNG) is considered to be a clean alternative fuel, and can be used as a replacement for gasoline and diesel, which reduces CO_2 emissions and provides a clean energy source for transportation [16]. CNG has a higher-octane number and knocking resistance than gasoline. As a result, CNG-dedicated engine can have higher compression ratios and, hence, higher efficiency. However, there are certain drawbacks, such as CNG having a lower flame speed that results in the higher temperature of engine components. Additionally, CNG has lower volumetric efficiency and energy density which reduces the output torque of the engine [17].

Although the researches mentioned above show some drawbacks in syngas, hydrogen and CNG, there are innumerable benefits to using these as fuels instead of fossil fuels. However, the current practice in the world still shows minimal development in alternative fuels because of its complex combustion process. So, this research uses Matlab simulation to compare the combustion parameters of syngas, hydrogen and CNG with gasoline fuel in the same conditions on a spark ignition engine. Here**,** MATLAB simulation is used to find the optimum alternative fuels for spark ignition engines with various operating conditions. Therefore, the study mainly focuses on comparing the multiple parameters of hydrogen, syngas and CNG with the current standard operating fuel, i.e., gasoline.

2. Materials and Methods

2.1. Methodology

A simulation based on mathematical modelling was obtained from the 4-stroke gasoline IC engine. In an engine-based mathematical simulation, combustion modelling plays a significant role.

Mathematical equations were inserted in the simulation, and then performance analysis was done on spark ignition engine of hydrogen, syngas and natural gas. The results were compared with gasoline as well. MATLAB code was developed for numerical simulation of various gases. The results obtained were compared with the conventional spark ignition engine.

2.2. MATLAB Simulation of SI Engines

Various equations were developed for varying compression ratio (CR), revolution per minute (RPM), spark advance and equivalence ratio. The modeling of mathematical equations divides the combustion chamber into various zones of burned and unburned gases and air/fuel mixture. MATLAB simulation was used to replicate the zone of combustion inside IC engine and thermodynamic activities in an accurate model-based simulation [18].

2.3. Engine Specification for Simulation

Table 1 shows the engine specification used in simulation

Specification of engine	Single cylinder, spark ignition, 4 stroke engine
Diameter of Bore (a)	0.0925 m
Length of Stroke (b)	0.1143 m
Length of connecting rod (l)	0.2286 m
Compression ratio (CR)	8:1-11:1
Engine Speed (RPM)	1500-4500

2.4. Air, Fuel, and Combustion Products Data

The curve fits constants range from a1 to a5 and there are 10 rows in one matrix. The constants ranging from a1 to a5 are the values of curve fits constant. There is a program called air data and fuel data in MATLAB simulation which provides the values of this curve fits constant for each simulation. These constants can be plotted using the curve-fit coefficients for equation 3.1 and 3.2 for all three gases.

$$\frac{C_p}{R} = a_1 + a_2T + a_3T^2 + a_4T^3 + a_5T^4 \tag{2.1}$$

$$\frac{C_p}{R} = a_1 + a_2T + a_3T^2 + a_4T^3 + a_5\frac{1}{T^2} \tag{2.2}$$

Where,

C_p = specific heat at constant pressure

R =Gas constant

T = Temperature

2.5. Calculation of Fuel-air-residual Gases Mole Fraction

A program called Fuel-Air-Residual Gases (FARG) determines the range coefficients for the curve using references from air data and fuel data programs. FARG operates for low temperatures ranging from 300 K to 1000 K. To determine the actual mole fraction, the moles of combustion gases inside the combustion chamber must be studied. A trace number of unburnt gases remain when exhaust stokes are complete. These leftover gases react with the new air/fuel mixture, and a new combustion process takes place. The species mole fraction for carbon dioxide (CO_2), nitrogen (N_2), hydrogen (H_2), carbon monoxide (CO) and water are given by the equation;

$$yi = \left(1 - y_r\right)y'_i + y_r y''_i, \quad i = 0\ to\ 6 \tag{2.3}$$

Where,

$\boldsymbol{y}_r$ = residual mole fraction

$\boldsymbol{y'}_i$ = reactant mole fraction = $\frac{n_i}{n_{fa}}$

$\boldsymbol{y''}_i$= product mole fraction = $\frac{n_i}{n_r}$

The FARG program determines the mole fraction of the actual gases taking part inside the combustion chamber and it requires certain parameters such as pressure, fuel type, equivalence ratio and mass fraction of residual gases.

2.6. Calculation of Equilibrium Combustion Products Mole Fractions

At elevated temperatures (600-3500 K) typical of combustion processes, the equilibrium state of the combustion products can be determined provided the mixture is not too rich ($0.3 \leq \Phi \leq 4$). A computer program, **ecpH2.m** is designed to calculate the properties of equilibrium combustion products for different fuel-air mixtures. For this program, ten product mole fractions are computed for equilibrium combustion of the fuel-air mixture with inputs specified such as temperature (T) in Kelvin, pressure (P) in kPa, fuel-air equivalence ratio (ϕ), and fuel id. The species included in the product mixture are CO_2, H_2O, N_2, O_2, CO, H_2, H, O, OH, and NO.

2.7. Homogeneous Two Zone Combustion Cycle

A program homogenous H2.m computes the heat and work of the system, heat loss from the system, mass loss from the system, and concentration of NOx, temperatures of burned and unburned fractions as well. Following are the simulation equations performed in the program.

$$\frac{dH_1}{d\theta} = \frac{Cm}{\omega}\left[\left(1 - x^2\right)h_u + x^2 h_b\right] \tag{2.4}$$

Where,

H_1= burned fraction

m= Combustible gas's mass

C = blow by coefficient

ω= engine frequency (rad/s)

x = mass fraction burned

h_u= Heat transfer coefficient (Unburned gas)

h_b= Heat transfer coefficient (Burned gas)

$$\frac{dP}{d\theta} = \frac{A+B+C}{D+E} \tag{2.5}$$

Where,

P = Pressure of the gas (kPa)

$A = \frac{1}{m}\left(\frac{dV}{d\theta} + \frac{VC}{\omega}\right)$

V= Volume of the cylinder (m^3)

$B = \frac{hA_c}{\omega m}[\frac{1}{c_{pb}}\frac{\partial v_b}{\partial T_b}x^{\frac{1}{2}}\left(T_b - T_w\right) + \frac{1}{c_{pu}}\frac{\partial v_u}{\partial T_u} - \left(1 - x^2\right)\left(T_u - T_w\right)]$

A_c= Cylinder Area (m^2)

c_{pb} = Constant pressure specific heat (Burned gas)

c_{pu} = Constant pressure specific heat (Unburned gas)

v_b= specific volume at unburned zone (m^3/kg)

T_b= Temperature of the combustible gas (Burned)

T_w= Temperature of cylinder wall (K)

v_u= Unburned zone's specific volume (m^3/kg)

T_u= Temperature of the combustible gas (Unburned)

$C =- \left(v_b - v_u\right)\frac{dx}{d\theta} - \frac{\partial v_b}{\partial T_b} - \frac{h_u - h_b}{c_{pb}}\left[\frac{dx}{d\theta} - \frac{\left(x-x^2\right)C}{\omega}\right]$

$D = x\left[\frac{T_b}{c_{pb}}\left(\frac{\partial v_b}{\partial T_b}\right)^2 + \frac{\partial v_b}{\partial P}\right]$

$E = (1 - x)\left[\frac{T_u}{c_{pu}}\left(\frac{\partial v_u}{\partial T_u}\right)^2 + \frac{\partial v_u}{\partial P}\right]$

$$\frac{dT_b}{d\theta} = \frac{-hA_C(T_b - T_w)}{\omega m c_{pb} x^{1/2}} + \frac{T_b}{c_{pb}} \frac{\partial v_b}{\partial T_b} \frac{A+B+C}{D+E} + \frac{h_u - h_b}{x c_{pb}} \left[\frac{dx}{d\theta} - \left(x - x^2\right) \frac{C}{\omega} \right] \quad (2.6)$$

Where,

T_b= Temperature of the burned gas (K)

h= convection heat transfer coefficient (W/m^{2}K)

$$\frac{dT_u}{d\theta} = \frac{-hA_C(1 - x^{\frac{1}{2}})(T_u - T_{W)}}{\omega m c_{pu}(1 - x)} + \frac{T_u}{c_{pu}} \frac{\partial v_u}{\partial T_u} \frac{A+B+C}{D+E} \quad (2.7)$$

Where,

T_u= Temperature of the unburned gas (K)

The graphs obtained after running the Homogenous H2.m program is mentioned below:

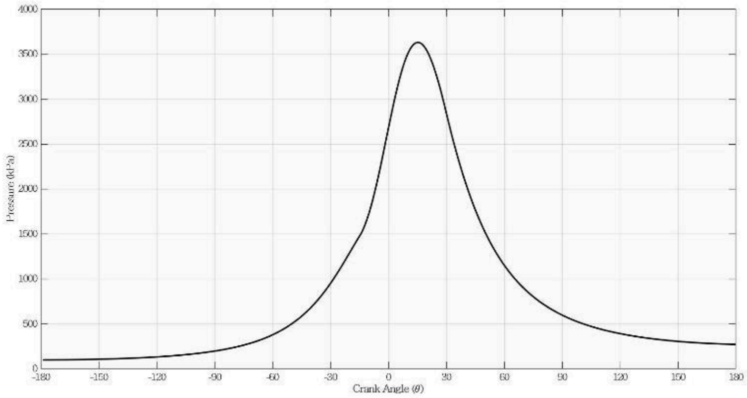

Figure 1: Pressure with respect to crank angle

2.8. Calculation for Hydrogen Composition

From the law of stoichiometry, the mole required for hydrogen and oxygen can be computed to have complete combustion as below;

$2H_2 + O_2 = 2H_2O$

Here, 2 moles of hydrogen react with one mole of oxygen for complete combustion which is theoretical approach. But air contains 70% nitrogen, so the calculation should be on this approach.

The number of moles of nitrogen in air on the basis of percentage is 3.76 moles. Thus, total number of moles of air has 4.76 moles of nitrogen. Here, oxygen weighs 32 gm and nitrogen weighs 3.76*28 i.e., 105 gm. Thus, total weight of air now becomes 137 gm. The weight of hydrogen is 4 gm.

Using law of reciprocal,

Air to fuel ratio for hydrogen and air is:

Air to fuel ratio based on mass: = $\frac{Wt. of\ air}{Wt. of\ Hydrogen}$ = $\frac{137.33}{4}$ = 34.33:1 (Gasoline is 14.7:1)

2.9. Calculation for Syngas Composition

For the calculation of C, H, O, and N, only the combustible gases present in the syngas are considered. Since the software demands only the atoms and compounds that take part in the combustion, the gases taken into account were CO, H_2 and Methane (CH_4) only.

In this, two different compositions for Syngas were taken by varying the composition of H_2, CO and CH_4.

Table 2: Composition of syngas

Gas	Syngas
H_2	11
CO	24
CH_4	3
CO_2	9
N_2	53

For Syngas,

The total percentage of CO, H_2 and CH_4 for Syngas (A) is

= (24+11+3) %

= 38%

Now, the proportion of these gases in the total combustible mass would be,

$CO = \frac{24}{38} = 0.632$

$H_2 = \frac{11}{38} = 0.29$

$CH_4 = \frac{3}{38} = 0.079$

Calculating the atom-based proportion we get, C = (0.632+0.079) = 0.71

H = (2*0.29+4*0.079) = 0.896

O = 0.632

The general chemical formula for Syngas (A) on the above calculation becomes, $C_{0.79}H_{0.896}O_{0.632}$

Carbon balance;

$C_{0.79}H_{0.896}O_{0.632} + O_2 = 0.71CO_2 + aH_2O$

Hydrogen balance;

$C_{0.79}H_{0.896}O_{0.632} + O_2 = 0.71CO_2 + 0.448H_2O$

Oxygen balance;

$C_{0.79}H_{0.896}O_{0.632} + 0.618O_2 \quad = 0.71CO_2 \quad + \quad 0.448H_2O$

(1 mole) (0.618 mole) (0.71 mole) (0.448 mole)

Therefore, 1 mole of syngas needs 0.618 mole of oxygen for complete combustion under combustion containing 0.71 mole of CO and 0.448 mole of water fuel, respectively. A mole of air has 0.21 mole of Oxygen

So, 0.618 moles of Oxygen is contained in = $\frac{0.618}{0.21}$mole of air

= 2.94 mole of air

The stoichiometric air-to-fuel (A/F) ratio will be 2.94:1. This is used as input data during the MATLAB simulation.

2.10. Calculation for Natural Gas

For the calculation of C, H, O, and N atoms, methane was used as natural gas since it only participates in the combustion process.

Table 3: Actual Composition of natural gas

Gas	Composition (%)
Butane (C_4H_{10})	1
Propane (C_3H_8)	1
Ethane (C_2H_6)	3
Methane (CH_4)	95

The total percentage of CH_4 is 95%

The atom-based proportion,

Carbon (C) = 0.95

Hydrogen (H) = 3.8

The general formula for natural gas from above calculation becomes,

$C_{0.95}H_{3.8}$

Carbon balance;

$C_{0.95}H_{3.8}+O_2=0.95CO_2+aH_2O$

Hydrogen balance;

$C_{0.95}H_{3.8}+O_2=0.95CO_2+1.9H_2O$

Oxygen balance;

$C_{0.95}H_{3.8}+1.9O_2=0.95CO_2+1.9H_2O$

Therefore, 1 mole of natural gas needs 1.9 moles of oxygen for complete combustion under combustion contains 0.95 moles of carbon dioxide and 1.9 moles of water per fuel, respectively.

1 mole of air has 0.21 mole of Oxygen.

So, 1.9 moles of Oxygen is contained in = 1.9

0.21 mole of air.

= 9.047 mole of air.

Then, the stoichiometric A/F ratio for natural gas will be 9.047:1.

This is also used as input data during MATLAB simulation.

3. Results and discussion

The simulation was performed for hydrogen gas, syngas and natural gas under various operating conditions using different parameters. The plot obtained from the simulation, along with the emission, is discussed below.

3.1 NOx Analysis

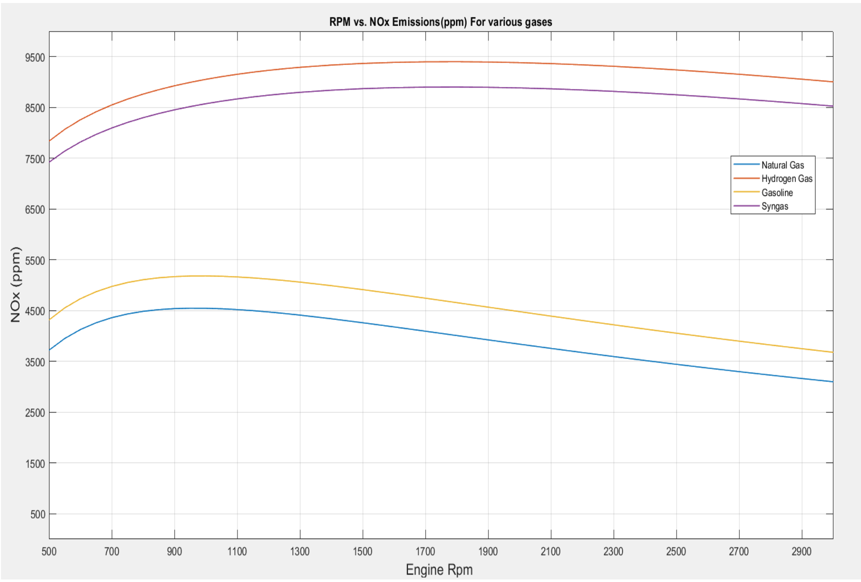

Figure 2: NOx vs Engine RPM of various gases at CR 8:1

The above graph represents the relation between NOx emissions in ppm with engine rpm of Natural gas, hydrogen gas, Gasoline and Syngas at CR 8:1 and an equivalence ratio of 0.8. It was found that

NOx emission contains high level of hydrogen and low levels of Natural gas. Hydrogen and Syngas have the most NOx emission at 1500 to 1700 rpm. Gasoline and Syngas have the least NOx emission from 1300 to 3000rpm, 4800 and 4500, respectively. The peak emission for hydrogen gas occurs at 1700 rpm and its value is about 9500 ppm. Similarly, for Syngas, the peak emission occurs at 1700 rpm, and its value is about 8500 ppm. From this, we conclude that hydrogen and syngas show similar properties for NOx emission from 500 rpm to 3000 rpm. Hydrogen has more NOx emission than syngas, gasoline and natural gas. NOx emission is, however, constant from 1700 to 3000 rpm for hydrogen and syngas, while NOx emission is gradually decreasing from 1700 to 3000 rpm in the case of gasoline and natural gas [11].

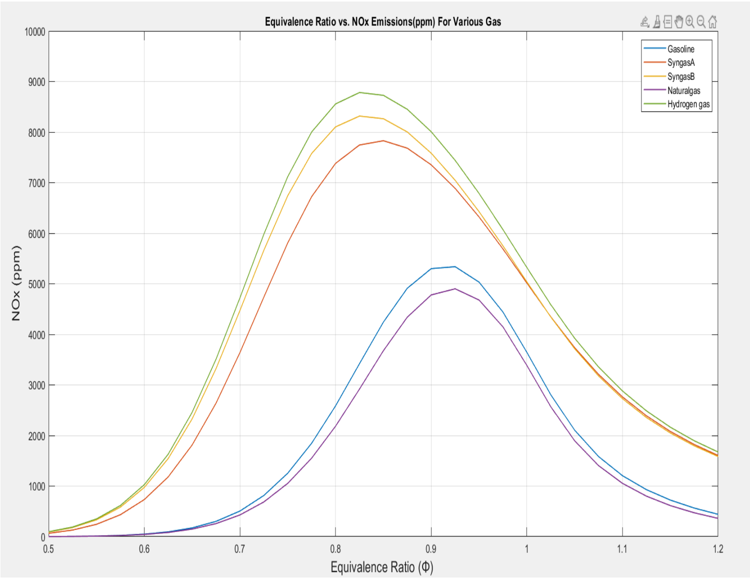

Figure 3: NOx Emission vs Equivalence ratio of various gases at CR 8:1

Figure 3 represents the relation between NOx emission and the equivalence ratio for hydrogen, syngas, natural gas, and gasoline at a compression ratio of 8:1 and speed of 1500 rpm. It can be found that NOx emission is higher in lean mixtures than in rich mixtures for all gases. However, it can be seen that gasoline and natural gas have maximum NOx emission from an equivalence ratio of 0.8 to 1 i.e. 5100 ppm and 4900 ppm, respectively, while syngas and hydrogen gas have maximum NOx emission from an equivalence ratio of 0.6 to 0.9, i.e. 8100 ppm and 8900 ppm respectively. It can be seen that for gasoline and natural gas, maximum NOx emission takes place during lean mixture. For hydrogen and syngas, NOx emission takes place during leaner mixture than gasoline and natural gas [13].

3.2 Cylinder Pressure Analysis

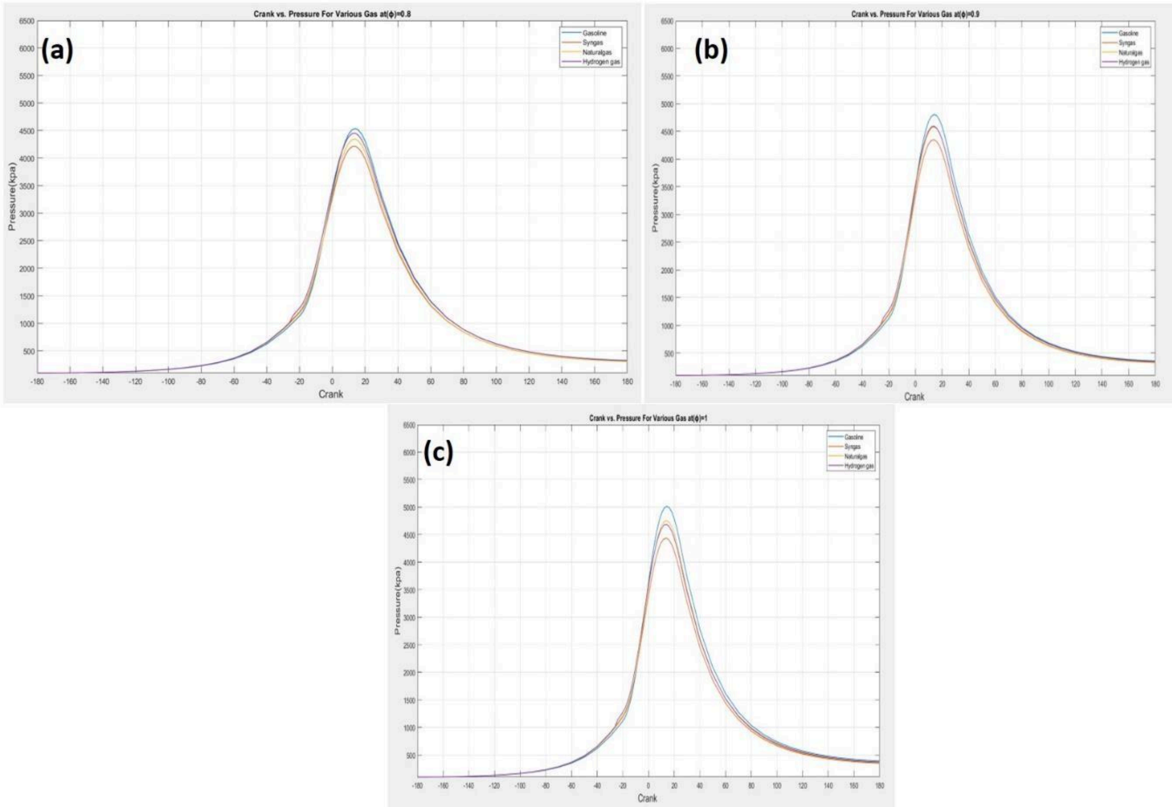

Figure 4: Pressure Vs crank angle relation of different gases at different equivalence ratio (a) ϕ = 0.8 (b) ϕ = 0.9 and (C) ϕ = 1

Figure 4 (a) shows cylinder peak pressure for gasoline, syngas, natural gas and hydrogen at compression ratio 8:1, spark timing 20°BTDC,1500 rpm and at equivalence ratio 0.8 with respect to crank angle. The peak cylinder pressure for gasoline is found to be 4500 kPa, while for syngas, it is found to be 4200 kPa and for natural gas, it is found to be 4300 kPa. The cylinder pressure for Hydrogen is found to be 4400 kPa. The cylinder peak pressure occurs at 18-20 degrees before the top dead center for all fuel, but the peak pressure of gasoline is higher in comparison to that of natural gas, syngas and hydrogen gas. This is because of the higher calorific value of the gasoline, and almost all the component are regarded as combustible, which produces much heat and, as a result, pressure increases. Natural gas has a higher peak pressure than that of syngas since it has a higher calorific value and contains more burning fuel. In contrast, syngas have a higher concentration of non-combustible gases in the fuel and a lower calorific value [12], [13].

Figure 4 (b) shows cylinder peak pressure for gasoline, syngas, natural gas and hydrogen at compression ratio 8:1, spark timing 20°BTDC, 1500 rpm and at equivalence ratio 0.9 with respect to crank angle. The peak cylinder pressure for gasoline and hydrogen is found to be 4800 kPa and 4600 kPa, respectively, while for syngas, it is found to be 4200 kPa and for natural gas, it is found to be 4600 kPa. The cylinder peak pressure occurs at 18-20 degrees before the top dead center for all fuel, but the peak pressure of gasoline is higher in comparison to that of natural gas, syngas and hydrogen gas.

Figure 4 (c) shows cylinder peak pressure for gasoline, syngas, natural gas and hydrogen at compression ratio 8:1, spark timing 20°BTDC, 1500 rpm and at equivalence ratio with respect to crank angle. The peak cylinder pressure for gasoline and hydrogen is found to be 4800 kPa and 4600 kPa, respectively, while for syngas it is found to be 4400 kPa and for natural gas, it is found to be 4700 kPa. The cylinder peak pressure occurs at 18-20 degrees before top the dead center for all fuel, but the peak pressure of gasoline is higher in comparison to that of natural gas, syngas and hydrogen gas [13].

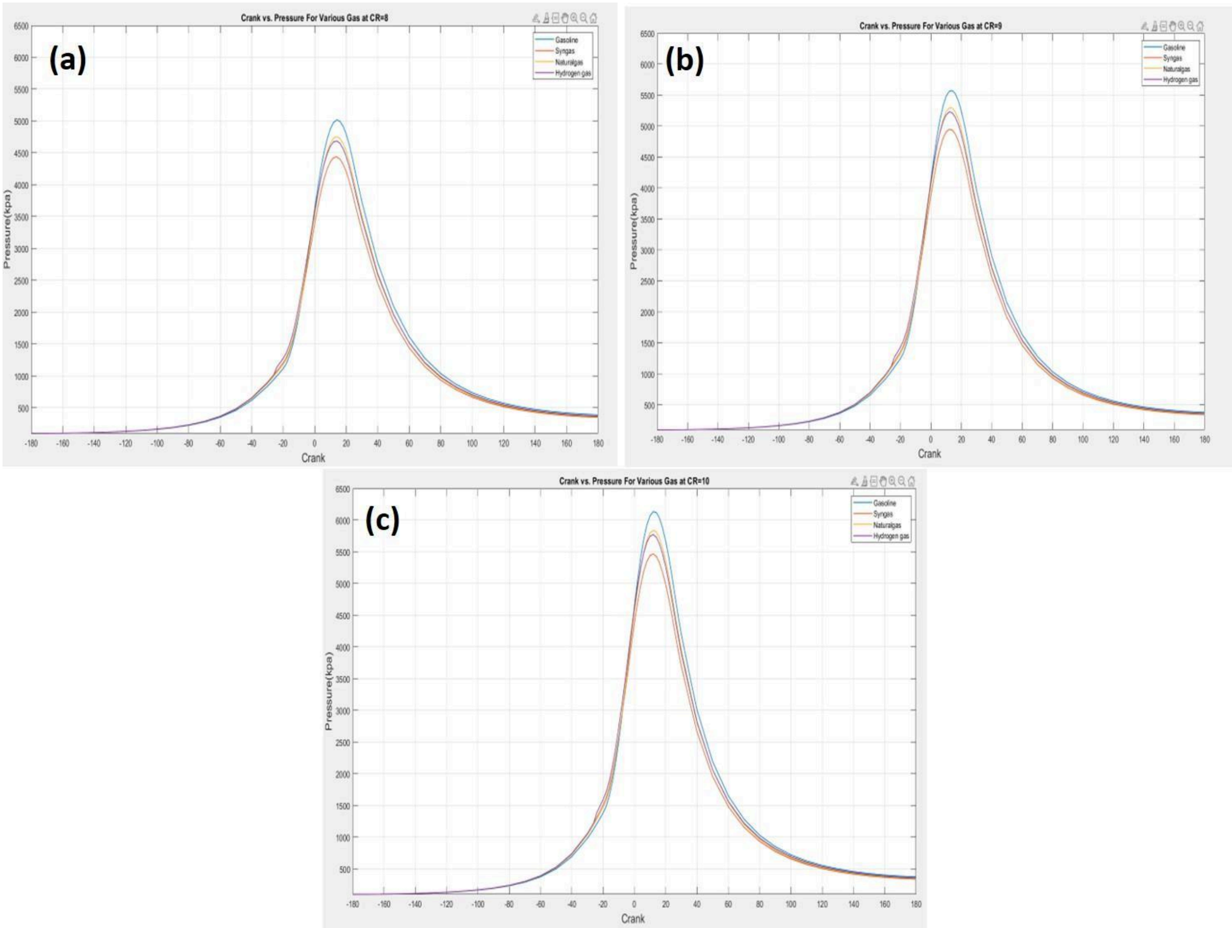

Figure 5: Pressure Vs crank angle relation of different gases at different compression ratio (a) CR = 8:1 (b) CR = 9:1 and (C) CR = 10:1

Figure 5(a) shows cylinder peak pressure for gasoline, syngas, natural gas and Hydrogen at compression ratio 8:1, spark timing 20°BTDC, 1500 rpm and at equivalence ratio with respect to crank angle. The peak cylinder pressure for gasoline and hydrogen is found to be 5000 kPa and 4600 kPa, respectively, while for syngas, it is found to be 4400 kPa and for natural gas, it is found to be 4700 kPa. The cylinder peak pressure occurs at 18-20 degrees before the top dead center for all fuel, but the peak pressure of gasoline is higher in comparison to that of natural gas, syngas and hydrogen gas.

Figure 5(b) shows cylinder peak pressure for gasoline, syngas, natural gas and hydrogen at compression ratio 8:1, spark timing 20°BTDC, 1500 rpm and at equivalence ratio with respect to crank angle. The peak cylinder pressure for gasoline and hydrogen is found to be 5600 kPa and 5200 kPa, respectively, while for syngas, it is found to be 4800 kPa and for natural gas, it is found to be 5300 kPa. The cylinder peak pressure occurs at 18-20 degrees before the top dead center for all fuel, but the peak pressure of gasoline is higher in comparison to that of natural gas, syngas and hydrogen gas [13].

Figure 5(c) shows cylinder peak pressure for gasoline, syngas, natural gas and hydrogen at compression ratio10:1, spark timing 20°BTDC,1500 rpm and at equivalence ratio with respect to crank angle. The peak cylinder pressure for gasoline and hydrogen is found to be 6200 kPa and 5700 kPa, respectively, while for syngas, it is found to be 5800 kPa and for natural gas, it is found to be 5600 kPa. The cylinder peak pressure occurs at 18-20 degrees before the top dead center for all fuel, but the peak pressure of gasoline is higher in comparison to that of natural gas, syngas and hydrogen gas [13].

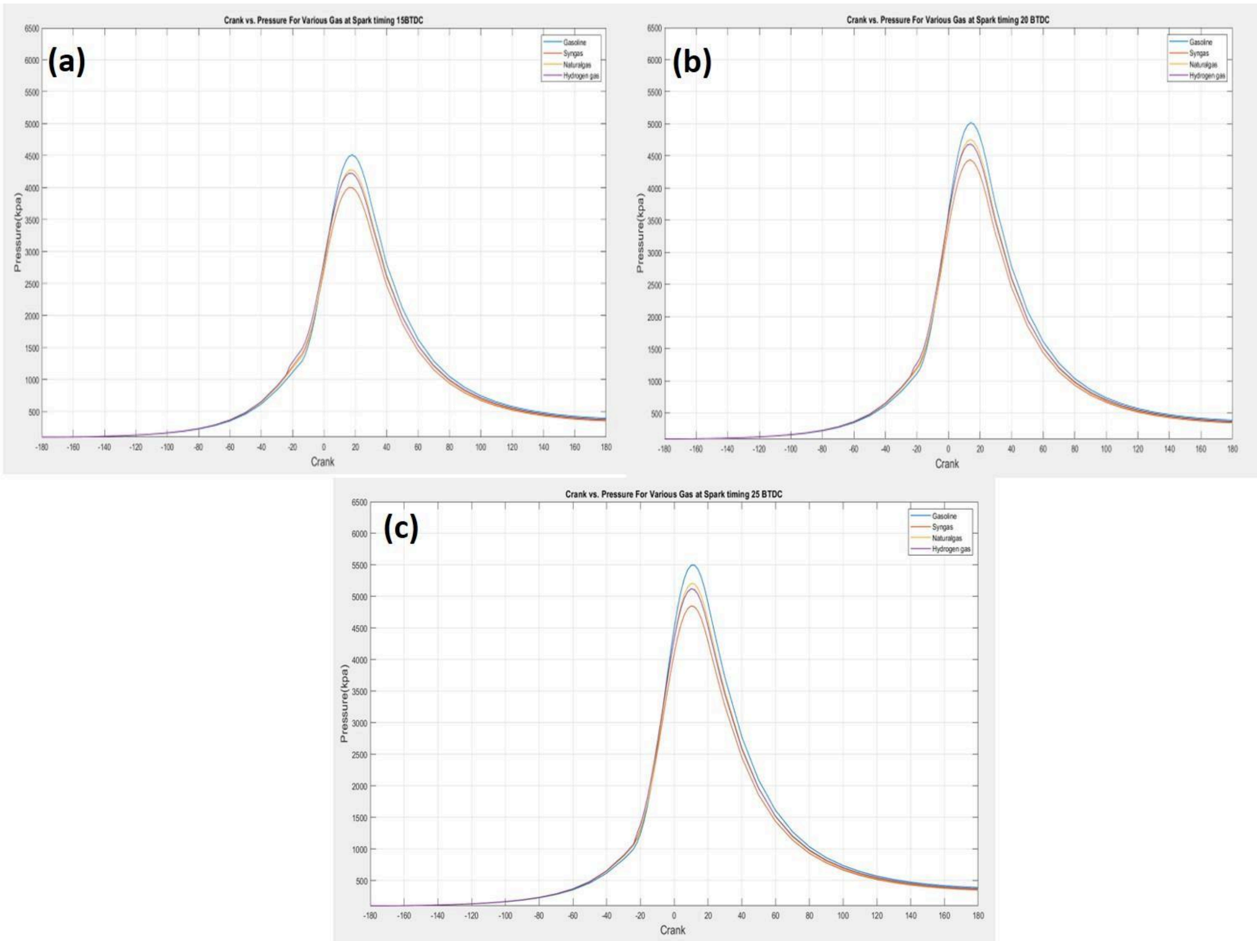

Figure 6: Pressure Vs crank angle relation of different gases at different spark timing (a) 15 BTDC (b) 20 BTDC and (C) 25 BTDC

Figure 6(a) shows cylinder peak pressure for gasoline, syngas, natural gas and hydrogen at compression ratio 8:1, sparktiming15°BTDC, 1500 rpm and at equivalence ratio with respect to crank angle. The peak cylinder pressure for gasoline and hydrogen is found to be 4500 kPa and 4200 kPa, respectively, while for syngas, it is found to be 4000 kPa and for natural gas, it is found to be 4300 kPa. The cylinder peak pressure occurs at 18-20 degrees before the top dead center for all fuel, but the peak pressure of gasoline is higher in comparison to that of natural gas, syngas and hydrogen gas. Decreasing the spark timing angle from 20 degrees to 15 degrees reduces the cylinder peak pressure.

Figure 6(b) shows cylinder peak pressure for gasoline, syngas, natural gas and hydrogen at compression ratio 8:1, spark timing 20°BTDC, 1500 rpm and at equivalence ratio with respect to crank angle. The peak cylinder pressure for gasoline and hydrogen is found to be 5000 kPa and 4700 kPa, respectively, while for syngas, it is found to be 4400 kpa and for natural gas, it is found to be 4750 kPa. The cylinder peak pressure occurs at 18-20 degrees before the top dead center for all fuel, but the peak pressure of gasoline is higher in comparison to that of natural gas, syngas and hydrogen gas. Increasing the spark timing angle from 15 degrees to 20 degrees increases the cylinder peak pressure.

Figure 6(c) shows cylinder peak pressure for gasoline, syngas, natural gas and hydrogen at compression ratio 8:1, spark timing 25°BTDC, 1500 rpm and at equivalence ratio with respect to crank angle. The peak cylinder pressure for gasoline and hydrogen is found to be 5500 kPa and 5200 kPa, respectively, while for syngas, it is found to be 4800 kPa and for natural gas, it is found to be 5250 kPa. The cylinder peak pressure occurs at 18-20 degrees before the top dead center for all fuel, but the peak pressure of gasoline is higher in comparison to that of natural gas, syngas and hydrogen gas. Increasing the spark timing angle from 20 degrees to 25 degrees increases the cylinder peak pressure.

4. Conclusion

A certain composition of syngas fuel and natural gas was taken for which a simulation was done varying different parameters such as spark timing, compression ratio and equivalence ratios. The results were then plotted and compared with gasoline. The major findings of the study are summarized as follows;

- Syngas has low specific heat capacity, so it needs less heat energy than natural gas and gasoline fuel to ignite. Natural gas requires less heat energy than gasoline to ignite. Hydrogen is highly flammable and requires the least heat energy to ignite. With the increase in hydrogen composition, the fuel will be more flammable.

- For the same input data, gasoline has higher peak pressure than hydrogen, natural gas and syngas, and syngas has lower peak pressure than hydrogen, gasoline and natural gas.

- Higher calorific value and higher concentration of combustible gases help to increase peak pressure more. So, gasoline has a higher peak pressure than hydrogen, syngas and natural gas with the same input.

- The peak pressure of hydrogen, gasoline, natural gas and syngas increases with increase of compression ratio, equivalence ratio (ϕ), and advanced spark timing.

- Hydrogen and Syngas can be run in both lean and rich conditions, which helps to reduce fuel consumption. This is not possible for gasoline and natural since gasoline and natural gas can run only at a stoichiometric air-fuel ratio.

- With the increase of engine speed, NOx emission at first increases and later decreases. NOx emission is found to be higher at the lean operating point ($\phi<1$) than at the rich operating point ($\phi>1$) since, at the lean operating point, there is enough availability of oxygen.

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6. **Declaration of interests**

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