The hydrogen-fueled SI engine: comparative analysis

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Hydrogen has been considered a prime candidate for the final destination as the world moves away from fossil fuels. It is found to be a suitable alternative fuel for spark ignition engines with the drawbacks of low power output and high NOx. In this study, a zero-dimensional multizones phenomenological model is used to study the performance characteristics and NOx and CO emissions of a four stroke Spark Ignition (SI) engine fueled by hydrogen, isoctane, gasoline and methane. The effect of doping hydrogen fuel up to 15% to gasoline fuel on the performance characteristics and emissions of a SI engine are studied. The tuning of the model is performed separately using experimental data, obtained in literature, for SI engine fueled by gasoline and hydrogen fuels keeping the same engine parameters, engine speed and air-fuel ratio to maintain simulation similarity. The combustion of hydrogen produces pure H_2O, easily making hydrogen the ultimate in "green" fuels. When it is combusted there are no emissions of carbon dioxide, carbon monoxide, or hydrocarbons. The study shows that the SI engine fueled by hydrogen produces lower brake power, brake specific fuel consumption (bsfc) and brake thermal efficiency compared with iso-octane, gasoline, and methane fuels. Supercharging is found to be a more effective method to increase the brake power of the hydrogen engine rather than increasing the engine compression ratio of the engine. Equivalence ratio and inlet pressure should be carefully chosen during the design of the hydrogen engine to achieve the best engine performance and minimum pollutant emissions. The results also show that enriching the gasoline fuel by up to 15% of hydrogen fuel decreases the brake thermal efficiency and increases the NOx emissions.

يعتبر وقود الهيدروجين مرشّح أساسي كوقود بديل عن الوقود الحفرى. و ثبت أنه يصلح وقود بديل مناسب لمحرّكاتِ اشعال الشرارةِ بعوائقِ مثل قلة القدرة الفرملية للمحرك وزيادة نسبة الاكاسيد النيتروجينية المنبعثة منه. في هذه الدراسةِ نستخدم كود كمبيوتر لا بعدى ذو المناطق المتعددة لدراسة خواص الاداء وانبعاثات اول اكسيد الكربون والاكاسيد النيتروجينية لمحرك اشعال بالشرارة رباعى الاشواط يستخدم وقود الهيدروجين والايزواوكتان و الجازولين والميثان. وتمت ايضا دراسة اضافة نسبة هيدروجين تصل الى 15% الى وقود الجازولين وبيان تاثيرها على اداء المحرك و انبعاثات العادم منه. و قبل اجراء الدراسة تمت مشابهة الكود مع نتائج عملية تم الحصول عليه من الدراسات السابقة مع الاحتفاظ بنفس ظروف التشغيل من سرعة المحرك و نسبة الهواء للوقود لتحقيق مضاهاه كاملة. ناتج حرق الهيدروجين هو الماء ولا يوجد اكاسيد الكربون او الوقود غير المحترق مما يجعلة من الوقود النظيف. اثبتت الدراسة ان محرّكِ اشعال الشرارةِ الذى يعمل بالهيدروجين يعطى قدرة فرملية اقل ومعدل استهلاك وقود اقل وكفاءة حرارية اقل مقارنة بوقود الايزواوكتان والجازولين والميثان. ووجد ايضا من الدراسة ان استخدام الحقن الجبرى للهواء اكثر فاعلية لزيادة القدرة الفرملية لوقود الهيدروجين من زيادة نسبة الانضغاط للمحرك. يجب اختيار معامل اغناء الوقود و ضغط دخول الهواء بدقة عالية لتحقيق افضل اداء واقل انبعاث للعادم لمحركات الهيدروجين. اثبتت الدراسة ايضا ان اغناء وقود الجازولين بنسبة تصل ال 15% من الهيدروجين تؤدى الى نقص القدرة الفرملية وزيادة انبعاثات الاكاسيد النيتروجيين فى غازات العادم مقارنة بوقود الجازولين.

Keywords: Hydrogen fuel, SI engine, Emissions, Engine performance

1. Introduction

Due to the pollution problems today and the energy crises, many researchers have concentrated on alternative fuels to decrease fuel consumption and lower the toxic emissions in the combustion products. Many investigations have studied the effect of using hydrogen as an alternative fuel (pure or mixed with another fuel) on engine performance and pollutants emissions [1-6].

Hydrogen is the only fuel that can be produced entirely from the plentiful renewable resource water, albeit through the expenditure of relatively much energy. Its combustion in oxygen produces only water, easily making

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hydrogen the ultimate in "green" fuels, but in air and high burnt temperature it also produces some oxides of nitrogen. These features make hydrogen an excellent fuel to potentially meet the ever increasingly stringent environmental controls of exhaust emissions from combustion devices, including the reduction of green house gas emissions [7]. Also it will be adapted to the more emission restriction which will be released in EURO 5 in 2008.

The hydrogen fuel when mixed with air produces a combustible mixture, which can be burned in a conventional spark ignition engine at an equivalence ratio below the lean flammability limit of a gasoline/air mixture. The flammability range of the hydrogen fuel is from 4% to 75% by volume while its value for gasoline fuel is from 1% to 7.6% by volume at atmospheric pressure. The resulting ultra lean combustion produces low flame temperatures and leads directly to lower heat transfer to the walls, higher engine efficiency and lower exhaust of NOx emission. Using hydrogen fuel rather than gasoline or isooctane fuels for short periods during cold starts and warm-up avoids problems of cold fuel evaporation. Using gasoline fuels may lead to uneven distribution of the fuel to the different cylinders due to the presence of a liquid film on the walls of the intake manifold and the unwanted large variations in supplied air–fuel ratio during transient conditions such as acceleration and deceleration [2].

Doping hydrogen fuel to gasoline fuel in internal combustion engines could be very interesting. In fact, premixed charges, based on gasoline enriched with small amounts of hydrogen, are characterized by wide flammability limits and a high flame velocity leading to good engine performance and reduced pollutant emissions [8, 9].

This paper focuses on studying the effect of three parameters that have a great effect on engine performance and emissions i.e., compression ratio, equivalence ratio and inlet pressure. Four types of fuels are considered i.e. hydrogen, isooctane, gasoline and methane. Also the effect of enriching gasoline fuel with up to 15% hydrogen fuel on engine performance and emissions is studied. Modeling work is carried out using the multizones phenomenological model concepts developed and implemented at Oxford Engine Research Group for simulation of engine studies [10] and premixed laminar flames combustion in closed vessel [11]. The model is first tuned with the experimental results obtained from the experimental program carried out on E6/US Ricardo Variable Compression Engine [2]. The model is found to give good agreement with the experimental engine brake power, brake specific fuel consumption (bsfc), NOx emissions and brake thermal efficiency for gasoline and hydrogen fuels. The model is used to study and to provide data on the effects of compression ratio, equivalence ratio and inlet pressure on engine power, brake thermal efficiency, bsfc, CO and NOx emissions of a supercharged engine operating on the above different fuels.

2. Multizones model

The simulation model used in the present study is a development of the multiple burned gas engine simulation model developed at Oxford Engine Research Group [10, 11]. Mathematical equations solved using the model in engine is given by Raine et al. [10] and for constant volume vessel for burning velocity calculations by Saeed and Stone [11]. In the present study, a four stroke spark ignition engine is investigated, therefore, the concepts developed above can be used for modelling. The zero-dimensional model use nitric oxides kinetics, friction model, heat transfer correlations, completeness of the combustion and different burn rate models, the details of which are provided by Raine et al. [10] and Saeed and Stone [11]. The different burn rate laws can be used but in the present study the cosine burn rate is found to give good tuning with the experimental data and hence is selected. The nitric oxide generation is investigated through the equilibrium burned gas and kinetic models. A ten-burned gas zones model is selected to model the combustion and the reason for its selection are discussed in the earlier study by Saeed et al. [12]. Ten- zones model is an extension of the two zones model of Ferguson [13]. A derivation of the two-zone model equations was extended to three zones (unburned plus two burned zones) and then to multiple zones. The equations for the multizones formulation are summarized by Raine et al. [10]. The mole fractions in each zone are weighted with the mass fraction burned to calculate the engine fully mixed emissions. In the present model, the unburned gas is assumed homogeneously mixed and the model is independent of spray shape or air motion. The model makes use of the assumption that the burned gas is in chemical equilibrium and the burned gas temperature, pressure, heat loss and work per degree of crank angle are calculated using the equation given in Raine et al. [10]. NO formation is calculated in every burned gas zone using the extended Zeldovisch NO mechanism and rate coefficient for NO kinetics provided by Raine et al. [10]. Table 1 shows rate parameters used in the present study.

The heat loss to the walls from the burned and unburned gas is modeled using the Hohenberg [15] and the frictional losses are modeled using the correlations of Chen and Flynn [16]. Equilibrium calculations are made using the Gordon and McBride ECP model [17] and the fuel coefficients used for the calculation of the charge properties for the pure and doped charge are presented in table 2. A method of obtaining these coefficients is described in detail in Saeed [18].

3. Engine specifications

The experimental data were obtained from a E6/US Ricardo variable compression engine used by Maher et al. [2]. The engine parameters used are the same as used by Maher et al. [2] to keep simulation similarity. The engine specifications and the conditions, at which simulation is run, are given in table 3.

4. Model validation

The model used in the present study is tuned with the experimental data to obtain the model results. The engine speed is kept constant at the conditions given by Maher et al. [2] for gasoline and Hydrogen fuel. Cosine burn rate law is used in the present study to simulate the rate of heat release, and the engine wall temperature is adjusted to tune the model with the experimental data of Maher et al. [2].

Fig. 1 shows the engine brake power versus the compression ratio while fig. 2 shows the engine brake power versus the inlet pressure (supercharged engine). A stoichiometric mixture and speed of 1500 rpm were used for both figures. It can be shown from the figures that the engine brake power from the ten-zones model is in good agreement with the experimental data with the variable compression ratio range from 7.5 to 10 and for the supercharged engine (inlet pressure varies from 1 bar to 1.8 bar). Also it can be seen from the results that the supercharging is a more effective method to increase the engine power of the hydrogen engine than increasing the compression ratio of the engine. The results in figs. 1 and 2 show good agreement between the experimental data and the numerical calculations with an average error less than 0.06% and 0.09%, respectively.

Table 1
Rate coefficients used, Heywood [14]

	A	B	E/R
O_2+ N2 ⇔ NO + N	1.6E+13	0	0
N+ O_2 ⇔ NO + O	6.4E+09	1	3160
N + OH ⇔ NO + H	4.1E+13	0	0

Table 2
Coefficients used for the calculations of charge properties

	Gasoline	Isocate	Hydrogen	Methane
A_0	4.0652	6.678E-1	0.30574451E+1	1.971324
B_0	0.060977	8.398E-2	0.26765200E-2	7.871586E-3
C_0	-1.88010E-05	-3.334E-5	-0.58099162E-5	-1.048592E-6
D_0	-35880.0	-3.058E+4	0.55210391E-8	-9.93042E+3
E_0	15.45	2.351E+1	-0.22997056E+1	8.873728

Table 3
Engine specifications, Maher et al. [2]

Number of cylinder	1
Bore	76.2 mm
Stroke	110.0 mm
Connecting rod length	241.3 mm
Cycle	Four stroke
Engine speed	1500 rpm
Compression ratio	variable
Ignition timing	variable

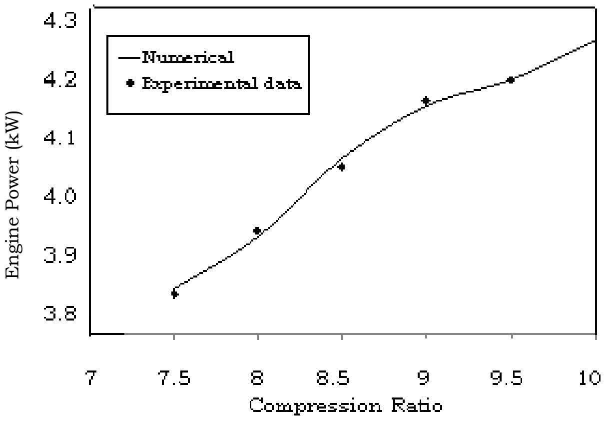


Fig. 1. The effect of the compression ratio on engine power for hydrogen fueled, inlet pressure = 1bar.

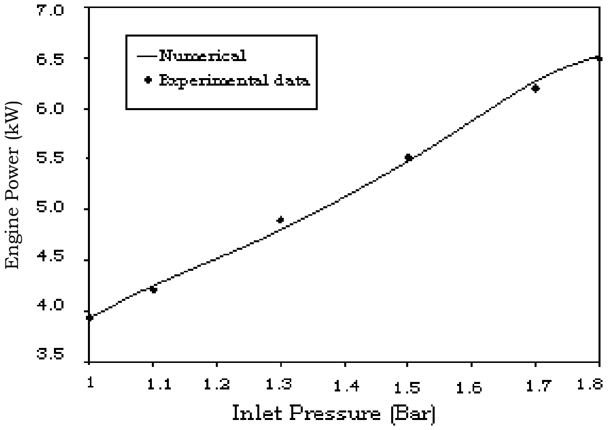


Fig. 2. The effect of inlet pressure on engine power for hydrogen fueled, compression ratio = 7.5.

Fig. 3 shows the results of the performance and emission comparison of the gasoline and hydrogen fueled engine (specific fuel consumption, brake thermal efficiency, and NOx). The compression ratio and engine speed were 7.5 and 1500 rpm, respectively. Each parameter studied is made dimensionless by relating it to its value for the unsupercharged gasoline engine for a stoichiometric mixture and compression ratio and engine speed equal 7.5 and 1500 rpm, respectively. The inlet charge pressure of the hydrogen engine is adjusted to produce the same power as that of the gasoline engine for a range of equivalence ratios [2].

It can be seen from the figure that the engine performance and emissions from the ten-zones model are in good agreement with the experimental data with the equivalence ratio range between 0.4 and 1. The average errors for fig. 3-a, b, c are less than 0.09%, 0.22% and 2%, respectively.

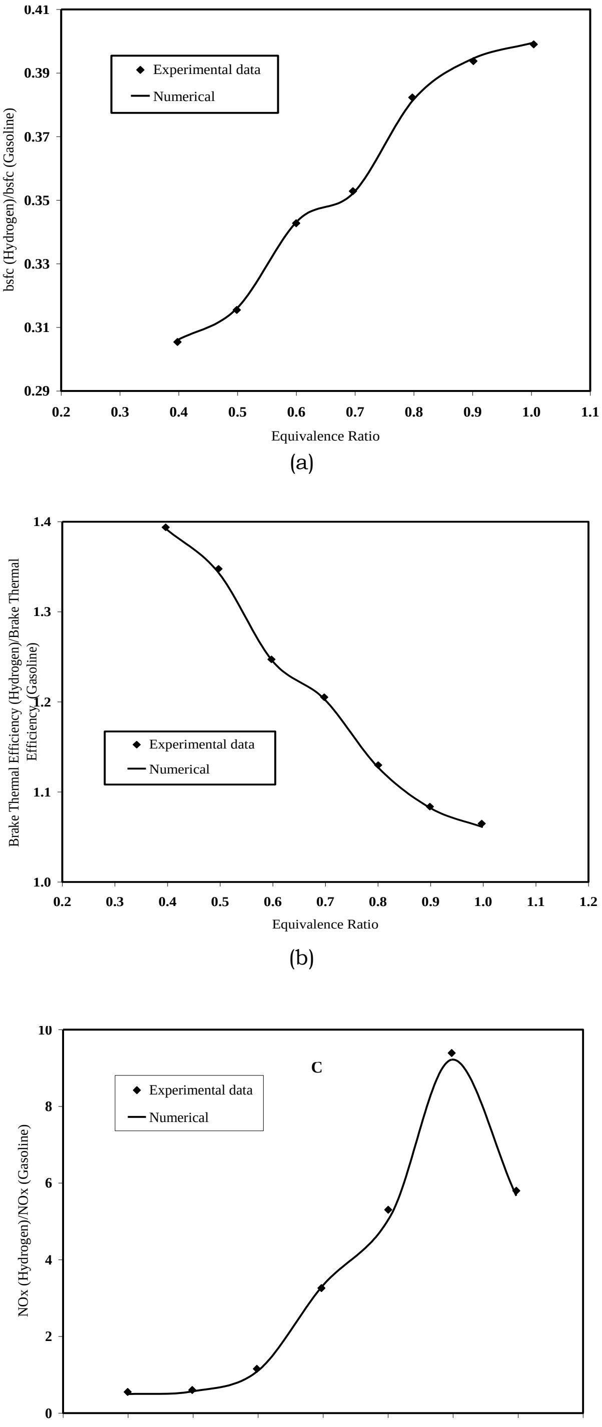
It can be concluded that, for the same operating conditions the hydrogen fueled engine generally produces lower maximum power and higher NOx emissions compared with the gasoline engine due to the restricted airflow and the higher maximum burnt temperature inside the cylinder, respectively [2]. The hydrogen fueled engine should be operated with lean mixture to reduce the NOx emissions. This condition gives lower power compared with that of a pure gasoline operation but with lower levels of NOx emissions as well. This lower power can be compensated by using a supercharged hydrogen fueled engine as explained in fig. 2.

The limitation of increasing the inlet pressure is to allow pre-ignition to be occurred in the engine where a reduction in both brake power and thermal efficiency is occurred. So the inlet pressure should not increase over 1.8 bar [2].

5. Results and discussion

5.1. Effect of compression ratio on engine performance and emissions

Fig. 4 shows the effect of the engine compression ratio on the engine performance (brake power, bsfc and brake thermal efficiency) and emissions (Nox and CO) at 1500 rpm engine speed for hydrogen, isooctane, gasoline and methane fueled. Equivalence ratio and inlet pressure were taken equal to 1 and 1 bar, respectively. It can be shown from the figure that, for the same



(a)

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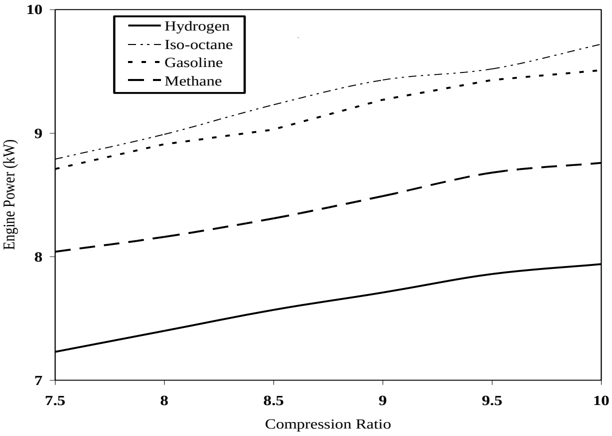
Fig. 3. The effect of equivalence ratio on engine performance and emission for gasoline and hydrogen fueled. Compression ratio =7.5.

operating conditions the hydrogen fueled engine generally produces lower brake power, bscf and brake thermal efficiency compared with the gasoline, isoctane and methane fueled engine in the range of compression ratio from 7.5 to 10. This can be attributed to the restricted airflow for the hydrogen fuel compared with the other fuels. Also, as expected, it can be seen that hydrogen fuel produces lower CO emissions (zero level) compared with the other fuels because it does not contain carbon atoms. Theoretically, the hydrogen fuel produces H_2O from the combustion with oxygen but CO may be produced from the hydrogen fueled engine due to the combustion of the burnt oil in the combustion chamber. Hydrogen fuel produces NOx emissions higher than gasoline and methane fuel due to the higher maximum temperature inside the cylinder.

Results similar to these shown in fig. 4 were obtained for compression ratio equals to 9.0 and the same conclusion was obtained. The results shown in fig. 4 agree with the results in Maher et al. [2].

5.2. Effects of equivalence ratio on engine performance and emissions

Fig. 5 shows the effect of equivalence ratio on engine performance (brake power, bsfc and brake thermal efficiency) and emissions (NOx and CO) for the same fuels used in fig. 4 at 1500 rpm engine speed. Compression ratio and inlet pressure were taken equal to 7.5 and 1 bar, respectively. The data in fig. 5 show that the hydrogen fueled produces the lower maximum brake power, bsfc and brake thermal efficiency compared with the isoctane, gasoline and methane fueled due to the restricted air flow for the range of equivalence ratio from 0.4 to 1.2. Also it can be shown that the hydrogen fuel produces maximum NOx emission due to the maximum burnt temperature of the hydrogen fuel as shown in fig. 6. Fig. 6 shows the burnt temperature versus crank angle for hydrogen, isoctane, gasoline and methane fueled engine at 1500 rpm engine speed. Equivalence ratio, compression ratio and inlet pressure were taken 1, 7.5 and 1 bar, respectively. It can be seen from the figure that, for the same operating conditions, the maximum burnt temperature of the hydrogen fueled is higher than the maximum burnt temperature of isooctane, gasoline and methane fueled by 7.2%, 8% and 8.5%, respectively.



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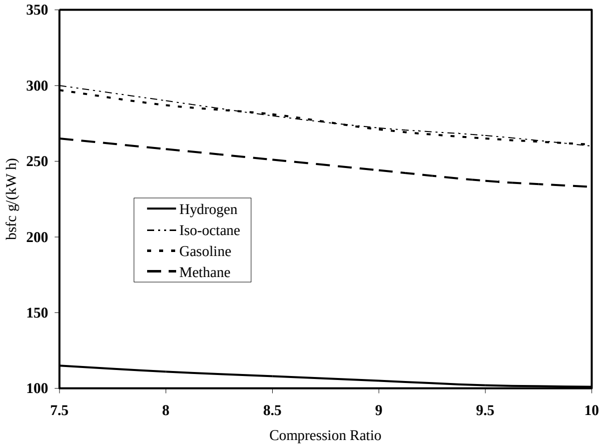

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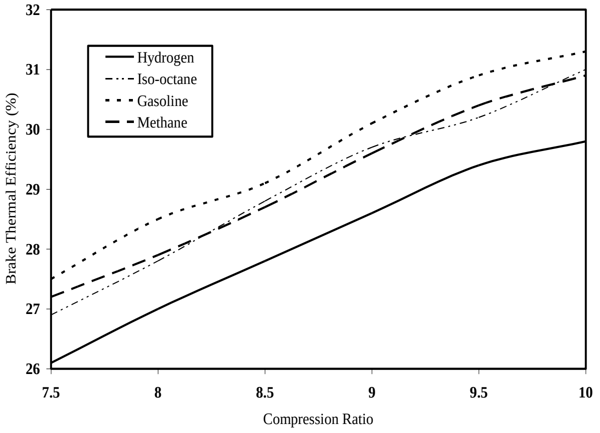

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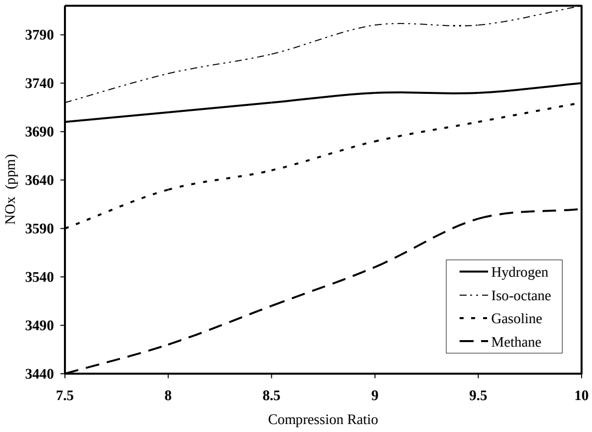

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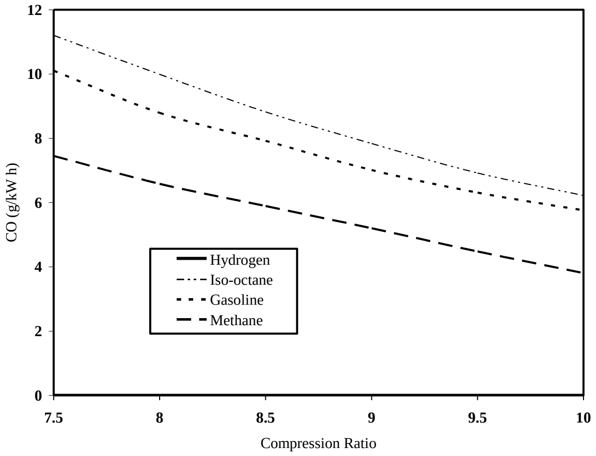

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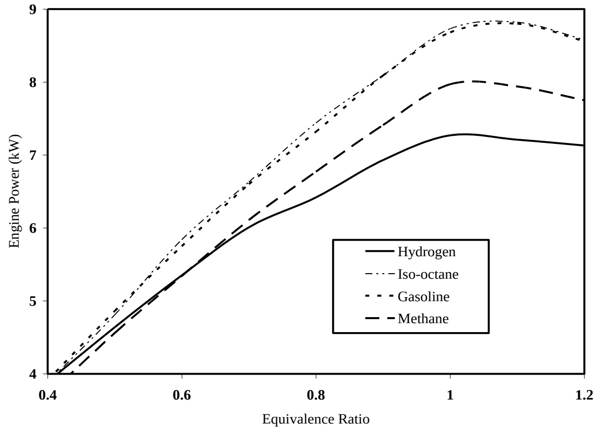
Fig. 4. The effect of compression ratio on engine performance and emission for hydrogen, isocatne, gasoline and methane fueled engine. Equivalence ratio =1, inlet pressure= 1 bar.

Results similar to these shown in fig. 5 were obtained for compression ratio equal 9 and they showed that the reduction in the amount of NOx emissions can be achieved by operating the engine with lean mixture. This can be attributed to the reduction in the burnt temperature which decreases the tendency of producing NOx emissions. Fig. 5-e shows that the level of CO emission starts to increase when the equivalence ratio exceed 1, as expected for isooctane, gasoline and methane fueled. Also it can be seen that hydrogen fuel produces zero CO because of the clean combustion in the whole rage tested for the equivalence ratio for the reasons explained in the above section.



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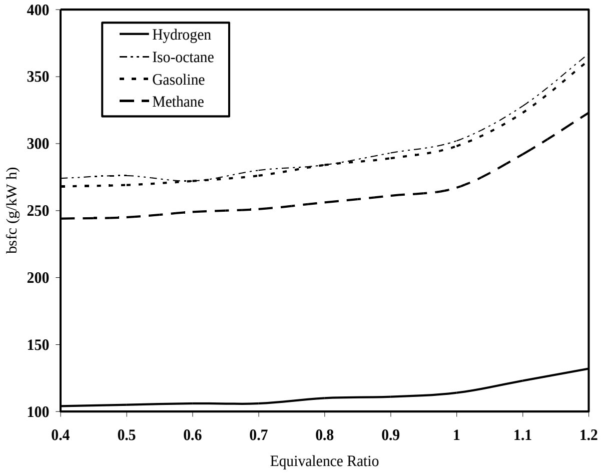

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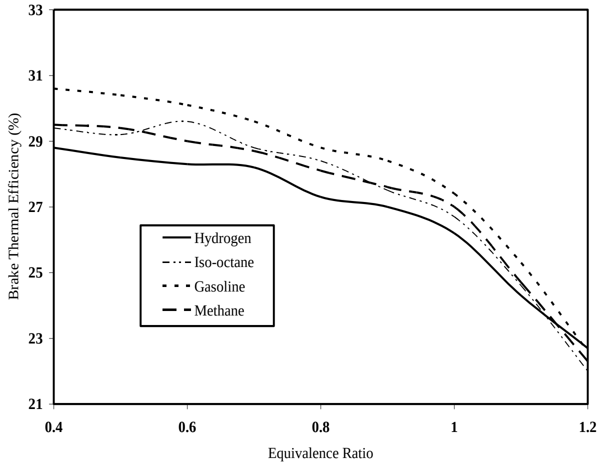

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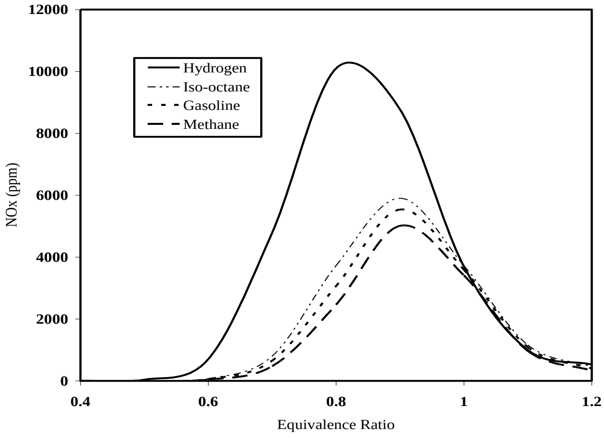

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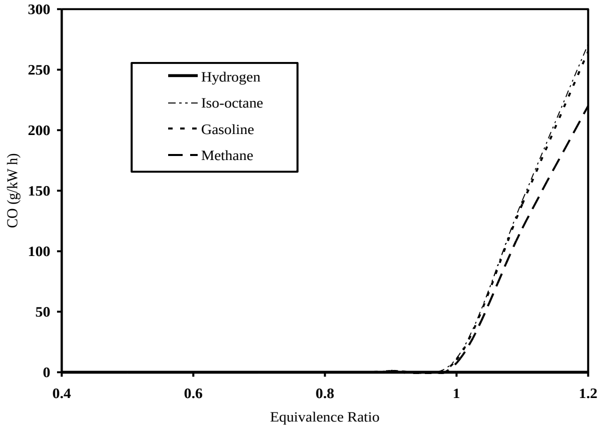

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Fig. 5. The effect of equivalence ratio on engine performance and emission for hydrogen, isocatne, gasoline and methane fueled engine. Compression ratio =7.5, inlet pressure = 1 bar.

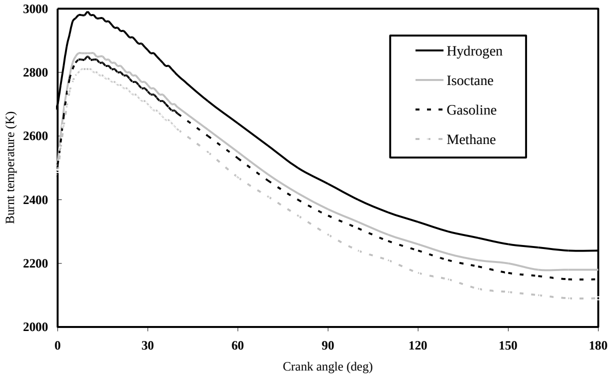


Fig. 6. burnt gas temperature versus crank angle for hydrogen, isooctane, gasoline and methane fuels. Equivalence ratio =1, inlet pressure =1 bar, compression ratio =7.5.

5.3. Effects of inlet pressure on engine performance and emissions

Fig. 7 shows the effect of inlet pressure (supercharging) on the engine performance and emissions for the same fuels used in fig. 5 at 1500 rpm engine speed. Both of the equivalence ratio and compression ratio were taken equal to 1. It can be shown from the figure that the hydrogen fuel produces the lower maximum power, bsfc and brake thermal efficiency and the higher NOx emissions when compared with the isocatne, gasoline and methane fuels for the range of inlet pressure from 1 to 3 bar. Increasing the inlet pressure from 1 bar to 1.8 bar increases the engine brake power by 80%, 78%, 77% and 79% for hydrogen, isooctane, gasoline and methane fueled, respectively. It can be concluded that increasing the inlet pressure of the charge can compensate the power reduction for the hydrogen fuel.

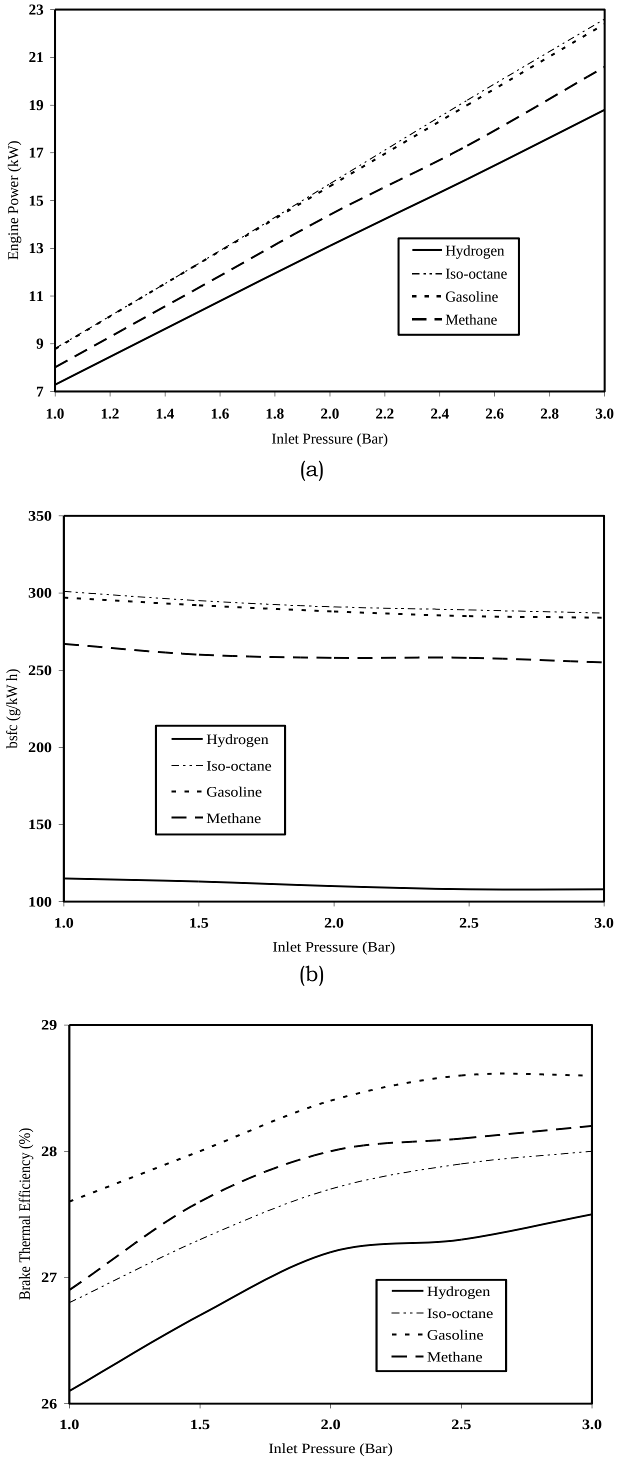
It can be seen from fig. 6 that, the effect of supercharging on hydrogen fueled is more significant than that on isoctane, gasoline and methane fueled for the same operating conditions.

It should be noticed that, increasing the inlet pressure over 1.8 bar lead to pre-ignition in the engine [2]. Therefore, the numerical results should be valid to 1.8 bar inlet pressure.

5.4. Influence of doping hydrogen to gasoline fueled on engine performance and emission

Adding a small amount of hydrogen to gasoline fuel in spark ignition engine leads to an increase of flammability limits and a high flame velocity for the blend, so that the engine can run with very lean mixtures, thus obtaining significant fuel economy [1].

Fig. 8 shows the effect of compression ratio on engine brake thermal efficiency and NOx emissions at 1500 rpm engine speed when hydrogen is added to gasoline fueled up to 15 %. The equivalence ratio and inlet pressure were taken equal to 1 and 1 bar, respectively. It can be shown from the figure that adding hydrogen fuel to gasoline fueled by up to 15% decreases the brake thermal efficiency by up to 1.5 % with an increase in the NOx emission by up to 0.3 % for the operating conditions taken in fig. 8 due to the increase of flammability limits and a high flame velocity for the blend compared with gasoline fueled.



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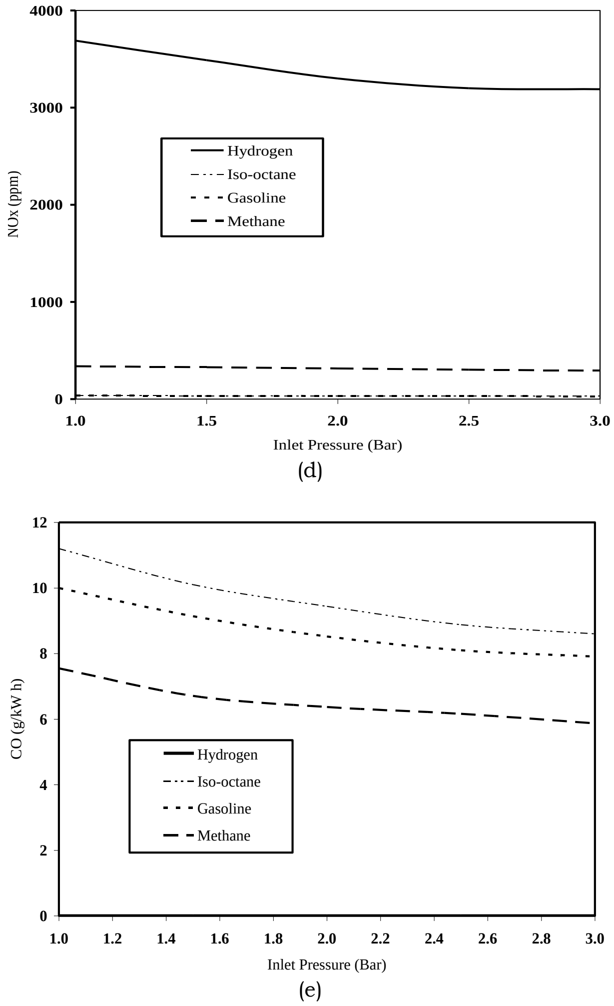

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Fig. 7. The effect of inlet pressure on engine performance and emission for hydrogen, isocatne, gasoline and methane fueled engine. compression ratio =7.5, equivalence ratio = 1.

6. Conclusions

The effect of compression ratio, equivalence ratio and inlet pressure on the performance characteristic and NOx, CO emissions of a four stroke spark ignition engine fueled by hydrogen, isoctane, gasoline and methane at varying engine operating conditions is obtained computationally. This is performed because it is very difficult and expensive to investigate this range of parameters experimentally. Also the effect of doping hydrogen fuel up to 15 % to gasoline fueled is investigated. From the present work, following conclusions can be drawn:

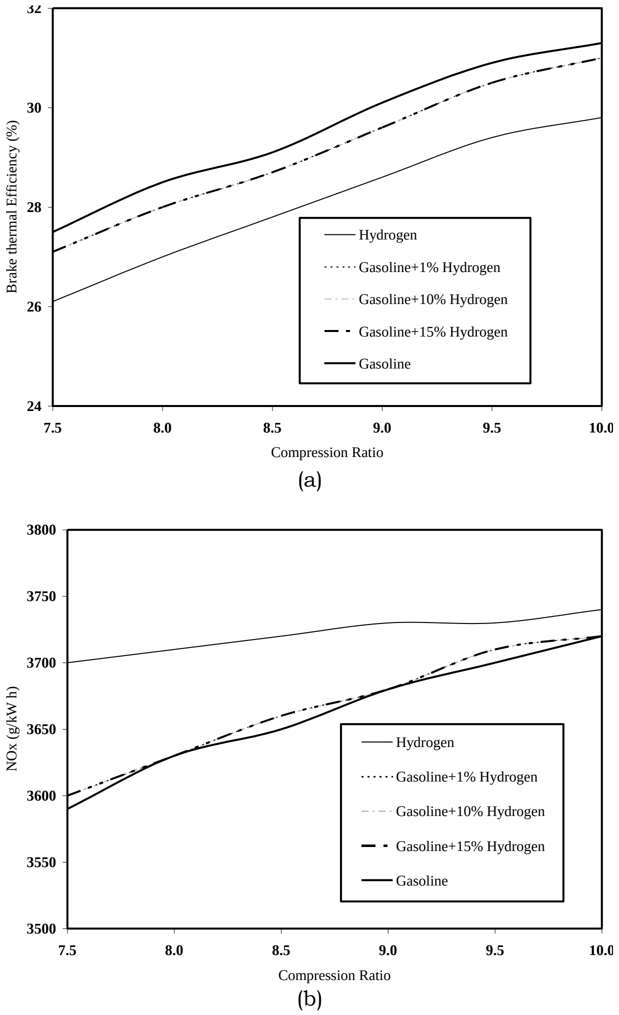

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Fig. 8. The effect of doping hydrogen fuel to gasoline fueled on engine performance and emission. Equivalence ratio = 1, inlet pressure= 1 bar.

- A multi-zones model developed at Oxford Internal Combustion Engine Research Group (ICEG) is tuned successfully with the experimental test data of E6/US Ricardo variable compression engine in Maher et al. [2].
- Multi-zones model establishes that compression ratio, equivalence ratio and inlet pressure have significant effect on engine performance and emissions and should be chosen carefully during the engine design to achieve minimum engine emission and best engine performance.
- Hydrogen fueled engine produces lower maximum brake power, bsfc and brake thermal efficiency with higher NOx emission

when compared with isoctane, gasoline and methane fueled.

- The power loss by using hydrogen fueled can be compensated by using supercharging. The effect of supercharging on hydrogen fueled is more significant than that on isoctane, gasoline and methane fueled for the same operating conditions.
- Doping hydrogen fuel up to 15% to gasoline fuel decreases the brake thermal efficiency by about 1.5% with an increase in the NOx emission by about 0.3% due to the increase of flammability limits and a high flame velocity for the blend compared with gasoline fueled.

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Definitions, Acronyms, Abbreviations

bsfc	brake specific fuel consumption
NOx	Oxides of Nitrogen
SI	Spark Ignition

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