VOL. 12, NO. 10, MAY 2017 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

THE EFFECT OF INCREASING THE PERCENTAGE OF HYDROGEN ADDED TO METHANE IN DIRECT INJECTION SPARK IGNITION ENGINE TO THE COMPOSITION OF CO AND CO_2 EMISSIONS

Mohd Radzi Abu Mansor[1], Hoo Choon Lih[1], Norhidayah Mat Taib[1], W. Ghopa Wan Aizon[2] and Zul Ilham[3]
[1]Department of Mechanical and Materials Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, UKM Bangi, Malaysia
[2]Centre for Automotive Research, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, UKM Bangi, Malaysia
[3]Institute of Biological Sciences, Faculty of Science, University of Malaya, Kuala Lumpur, Malaysia
E-Mail: radzi@ukm.edu.my

ABSTRACT

The emission of CO_2 has been dramatically increased within the last decade and is still increasing each year, making it the main cause of global warming. CO_2 is mainly created by burning fossil fuels such as petrol and diesel. One of the solutions to decrease the emission is by changing the use of petrol to alternative fuel such as Compressed Natural Gas (CNG) or hydrogen. CNG is primarily composed of methane and also contains ethane, propane and heavier hydrocarbons. Even though natural gas has the lowest carbon emission of all fossil fuel, it still has significant carbon content. On the other hand, hydrogen has no carbon content so the replacement of some percentage of natural gas to hydrogen will reduce carbon emission. This study was carried out in order to investigate the influence of increasing the percentage of hydrogen, as a substitute to methane, to the emission produced in the direct injection internal combustion engine conditions. The combustion of hydrogen-methane mixture was simulated by using Star-CCM+ CFD software. The design of the combustion chamber used is similar to the condition for the combustion of petrol in an internal combustion engine where all the valves were closed. The emission of CO and CO_2 from the combustion was observed. The emission results of the percentage of hydrogen added to methane fuel was analysed and discussed. The results showed a decrease of carbon monoxide and carbon dioxide emissions with the increase of hydrogen percentage. This shows that hydrogen-methane mixture has a high potential to be used as the alternative combustion strategy in transportation to replace the existing non-renewable fuels and potentially able to reduce the greenhouse gas problem.

Keywords: hydrogen, methane, CNG, emissions.

INTRODUCTION

Limited energy resources and the importance of preserving the environment have gained attention from researchers around the world. This has lead to the research in improving the efficiency of combustion as a source of energy and to reduce harmful exhaust emission mainly produced from the transportation sector to the environment. A research in[1] stated that, the petroleum source around the world would be exhausted in the next 50 years. Therefore, renewable energy sources are expected to replace these fossil fuels. Exploration of alternative fuels is essential to replace the existing fuel such as diesel and gasoline since the fuel market price keeps increasing and has become a burden to customers. An internal combustion engine often operates using gasoline which leads to pollution problem.

Compressed Natural Gas, also known as CNG, is said to be the cleanest burning fuel and are being used as fuel for commercial engine. CNG is also known as the cheaper fuel compared to petrol. CNG is a mixture that exist in gas phase during operation that can contains up to 99% methane and 1% other gases such as carbon dioxide, nitrogen and hydrogen sulphide, depending on the location of the source of the natural gas. CNG produces lower CO and CO_2 emission because its chemical structure is simple [2] and contains less number of carbon. CNG is stored at gas phase in low temperature (-161˚C) therefore, CNG is able to be used at gas phase during operation [3]. CNG also contains high number of octane that allows engine to operate on higher compression ratio. This leads to high power output and thermal efficiency of the engine [2].

Moreover, its auto ignition temperature (around 540˚ C) is higher than gasoline and able to reduce the combustible rate and explosive should there be any leakage [3]. It also has lower density and properties of a physico-chemical which makes CNG an excellent fuel for spark ignition engine. However, its combustion velocity was discovered to be very low and has lower lean abilities that can cause incomplete combustion, high misfire ratio and large cylinder changes during lean mixture combustion. Therefore, the addition of hydrogen to CNG will be able to improve the combustion characteristics since hydrogen, also known as the secondary fuel of the future, would produce a combustion that is free from carbon and only produce water as main product. Hydrogen also provides higher combustion velocity at the rate of 7 times higher than other mixtures [2].

Energy policy experts also argue that the use of hydrogen as fuel in the transportation sector in the internal combustion engine is better than in fuel cell for a period of several decades of use. Although there are still some obstacles in the use of hydrogen in transportation sector, the result from [4] research shows that the production, distribution and hydrogen storage is achievable.

Hydrogen-fueled engine can also be operated with very lean mixture flammability [5] and [6] as large as the lower limit of 4% and an upper limit of 75%. This capability allows an adjustment to be made to alter the composition of the burden mixture content without depending on the throttle valve. It will also increase the overall efficiency of the engine due to the absence of flow loss and better combustion efficiency at high λ value [7]. Hydrogen can also improve the ignition energy of fuel and it is able to reduce engine misfire [8] and improve the engine performance [9] as shown in Figure-1. The low ignition energy of hydrogen combustion indicates that hydrogen in internal combustion engine are predispose towards the limiting effects of preignition [9]. Hydrogen can also speed up the flame propagation and reduce quenching distance [10], thus decreasing the possibilities of incomplete combustion and at the same time reduce the emissions of CO and CO_2 [11]. CO content was proven to cause a bad effect to the engine since it reduces the combustion duration of gas [12] and [13]. Hydrogen production method can be divided into two categories which is converting molecules into hydrogen and by electricity consumption. Furthermore, hydrogen can also be produced by fossil fuel conversion. However, it could bring some impact to the environment due to the high emission of carbon dioxide during its production [14]. Therefore, the production of hydrogen is best continued using biomass processing and other renewable resources to maintain its natural stability.

The emissions resulting from the combustion of hydrogen-methane with air usually produce carbon dioxide, carbon monoxide, nitrogen oxide (NOx) and solid carbon that formed due to the incomplete combustion. Solid carbon emission related to the combustion temperature where the unburned hydrocarbon was reduced due to the local combustion temperature [15].

The formation of NOx is highly dependent on temperature and duration of combustion at high temperatures. The rate of formation of NOx increased rapidly with increasing temperature. Therefore, the formation of NOx need to be avoided or delayed by keeping the combustion temperature below 1800K [15]. The emission of carbon dioxide and carbon monoxide also produces lower emission from the hydrogen combustion. Therefore, hydrogen was proved by the previous researcher as the cleanest fuel.

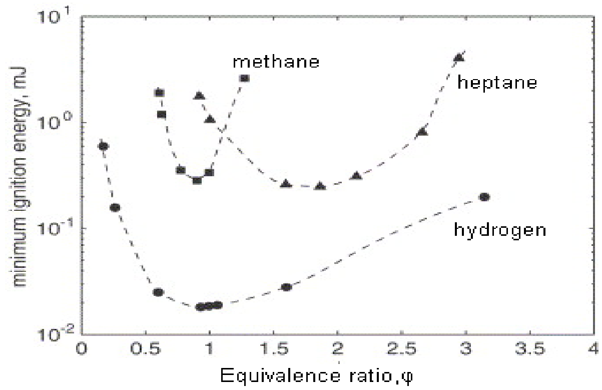

Figure-1. Minimum ignition energy of hydrogen, methane and heptane combustion [9].

The composition factors of mixed hydrogen in methane gives a uniform increment in hydrogen to carbon ratio (H/C) where it is able to reduce the emission of CO, CO_2 and hydrocarbon [16]. Hydrogen-CNG mixture is also able to reduce hydrocarbon and carbon monoxide concentration with the increase of hydrogen. This is because this emission is related with the air fuel ratio. Hydrogen replacement in CNG is also able to reduce the emission of NOx due to the low temperature at low engine loads and high excess air ratio [2].

Hydrogen has many advantages compared to other fuels in internal combustion engine. Hydrogen is a unique fuel that is able to improve the efficiency of combustion, engine power output and reduce exhaust emissions that causes pollution. However, the use of hydrogen must be performed under the right operating conditions due to the high burning velocity that may lead to the emission of NOx. A guaranteed and low emission is the important issue in order to reduce pollution.

Since methane gas is the major composition in natural gas, the composition of natural gas was assumed as 100% methane in this study. From this research, the composition percentage of carbon dioxide and carbon monoxidefrom the combustion of direct injection of internal combustion engine can be determined according to the change of percentage of hydrogen and methane mixture. Moreover, this research also aims to compare the emission of carbon dioxide and carbon monoxide between the usage of 100% methane and hydrogen-methane fuel mixture.

METHODOLOGY

Computer Fluid Dynamics (CFD) was used to analyze the fluid flow and heat transfer to obtain the composition of the combustion exhaust emission of 100% methane and the addition of hydrogen into methane in direct injection internal combustion engine. The analysis is developed in 3D modeling with the assumption of steady flow, obeys the ideal gas law and public K-epsilon, non-pre-mixing, and turbulence flow. The 3D engine model was developed using CATIA software and imported to one of the commercial CFD software Star-CCM+ to analyze the thermal flow of the gas in internal combustion engine.

Table-1. Engine specification for modified CAMPRO 1.6L engine.

Features	Descriptions
Engine capacity	1596 cc
Stroke	76.0 mm
Bore	88.0 mm
Connecting Rod	131 mm
Compression ratio	14
Crank radius	44 mm
Number of valve	16

The combustion chamber was designed according to the specification of a modified CAMPRO 1.6L engine. The bore and stroke is 76 mm x 88 mm. The engine specification is explained in Table-1. The engine was initially constructed for petrol use with a port injection method and some alterations were done to the engine in order to operate using direct injection gaseous fuel strategy [17]. The simulation is only performed for a single cylinder engine at 2000 rpm. This research is mainly focused on the combustion chamber area under the cylinder head. The ignition power stroke begins at 20˚ BTDC. Therefore, the simulation is conducted for three models at TDC, 10˚ ATDC, and 20˚ ATDC during combustion reactions at a certain velocity, pressure of 4.5 MPa and temperature of 1000 K.

Based on the cylinder details, initial velocity calculations for all mixtures were determined by using Equation. 1.

$$S_p = 2Ln \quad (1)$$

Where
L = stroke (mm)
N = number of revolution per cycle

Computational analysis using CFD codes provides details of the process in the cylinder which allows the reduction of the manufacturing cost, test and measurement data. The process of CFD simulations begins with preprocessing, followed by solution and ends with post processing. Seven gas components namely CH_4, O_2, CO, H_2, CO_2, H_2O and N_2 are set as the initial gas properties in determining the emissions level in combustion. During this process, all boundary condition for all models were set in adiabatic condition. The simulation was observed for only 10 iterations because in internal combustion engine, the combustion rate of fuel/air occurs very fast. Table-2 shows the regulation and reference value of model and gas characteristics.

Table-2. Model regulations and liquid properties of combustion operation.

Ref. pressure	1.0 atm
Ref. temperature	293 K
Max. iterations	10
Fluid model	Turbulent flow
Dynamic viscosity (air)	Constant
Therm. conductivity (air)	Lewis number
Dynamic viscosity (H2, CH_4)	Constant
Model movement	Static
State	Ideal gas
Type of fuel mixing	Pre-mixing

For post processing, the results from Star-CCM+ was displayed by scalar bar that provides the minimum and maximum values for the selected criteria in order to observe the contours of the combustion. The simulation was conducted using 3D model with the assumption of 100% methane composition with air ratio of 23.3% oxygen and 76.7% nitrogen. The analysis was continued by reducing the percentage of methane and the addition of 10%, 20% and 30% of hydrogen.

RESULTS AND DISCUSSIONS

Three additional hydrogen percentages were selected in replacing 100% methane fuel to investigate the effect to CO and CO_2 emission. The simulation was performed by using different percentages of hydrogen-methane composition where some percentage of methane was replaced by hydrogen in composition of 0%, 10%, 20% and 30% and was conducted at TDC, 10˚ ATDC and 20˚ ATDC. The simulation was conducted for 10 iterations in combustion engine with 2000 rpm with 0.015s per stroke. Some fuel mixture ratio was simulated to study the effect of substitution of hydrogen to methane. Based on the result obtained from Star-CCM+ software, the emission concentrations of CO and CO_2 were observed.

Result of the combustion simulation for the fuel mixture composition

Figure-2 shows the comparison of emission concentration of CO and CO_2 at TDC, 10˚ ATDC and 20˚ ATDC for 0% hydrogen (100% methane). The color contour shows the mole fraction of the emissions inside the combustion chamber. Two ports that were connected on the left of the model is the intake ports while the right port on the model is the exhaust port. A small hole located between the intake port and exhaust port acts as the parallel fuel injector for the ignition. A contour with high emission concentration was found in the area near the injector. This is due to the combustion reaction between fuel and air which initially started near the injector area.

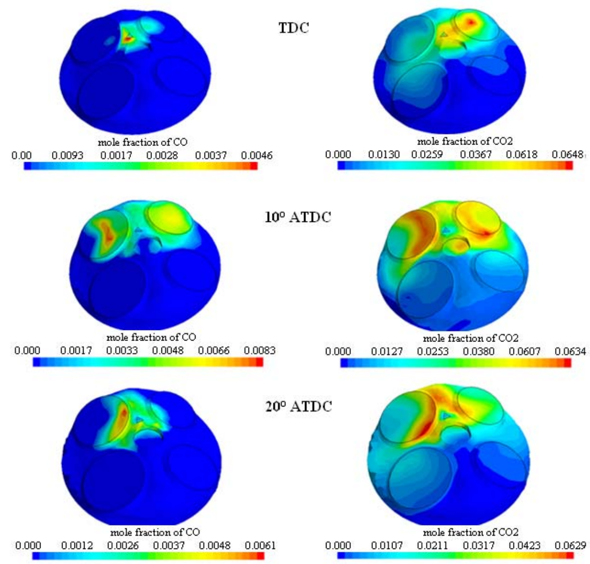

Figure-2. Mole fraction of CO and CO_2 at TDC, 10˚ ATDC and 20˚ ATDC for 100% methane.

However, the contours of emission was found not extended to the whole volume of the combustion chamber because the simulation was performed at the end of the compression stroke and the beginning of power stroke. The colour bar shows the different pattern of CO and CO_2 emissions where both mole fraction of CO and CO_2 has increased when the piston move downwards. At 20˚ ATDC, the emission concentration of CO_2 was observed to decrease near the cylinder head area but the total amount of CO_2 in combustion chamber has increased. This is because the simulation only focused at the area from the view of the cylinder head. It is believed that the emission of CO_2 at 20˚ ATDC is the highest emission because when the piston move downwards during expansion, the emission of CO_2 moved to the lower part of the combustion chamber area. Generally, the emission of CO_2 is increased at higher crank shaft angle.

Figure-3 shows the comparison between mole fraction of CO and $CO_2$for 10% hydrogen and 90% methane at 20˚ ATDC. From the contour result, the mole fraction of CO_2 has decreased when 10% of hydrogen was added. The results were then compared to Figure-4 and Figure-5 for 20% and 30% of hydrogen percentage at the same condition of 20˚ ATDC. The colour bar indicates that the mole fraction of CO and CO_2 has both decreased when percentage of hydrogen added to the methane fuel was increased.

Figure-6 shows the result in percentage for the maximum concentration of CO_2 and CO emission acquired based on the percentages of hydrogen added at TDC, 10˚ ATDC and 20˚ ATDC. The graph indicates that the higher the percentage of hydrogen added, the lower the emission of carbon monoxide and carbon dioxide gas acquired. Moreover, the result also showed that the higher the percentage of hydrogen added into methane, the higher the hydrogen to carbon ratio produced because the content of carbon in the fuel mixture was reduced. Reduction of carbon content in fuel leads to a potentially lower production to carry out the reaction of carbon monoxide and carbon dioxide since the reactant are limited. Therefore, the emission amount of carbon was reduced. However, at some point of the additional hydrogen percentage, there are some increment of carbon dioxide and carbon monoxide emission. This might happen due to the temperature changes that affect the reaction in carbon monoxide and carbon dioxide production.

The emission of carbon monoxide and carbon dioxide from the combustion of hydrogen-methane was less than the emission produced from the combustion of 100% methane fuel. A general view of the graph shows the addition of hydrogen in methane has resulted in the reduction of carbon dioxide and carbon monoxide emission.

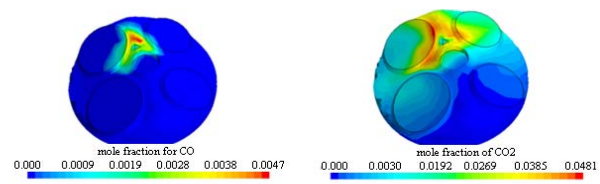

Figure-3. Mole fraction of CO and CO_2 for 10% hydrogen, 90% methane at 20˚ ATDC.

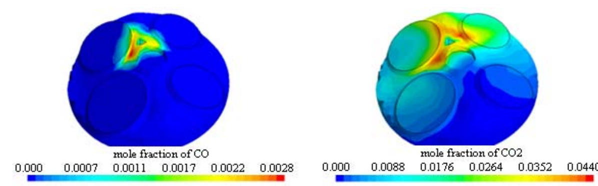

Figure-4. Mole fraction of CO and CO_2 for 20% hydrogen, 80% methane at 20˚ ATDC.

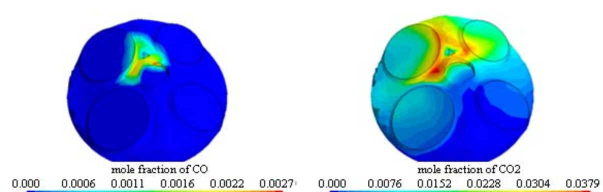

Figure-5. Mole fraction of CO and CO_2 for 30% hydrogen, 70% methane at 20˚ ATDC

ARPN Journal of Engineering and Applied Sciences

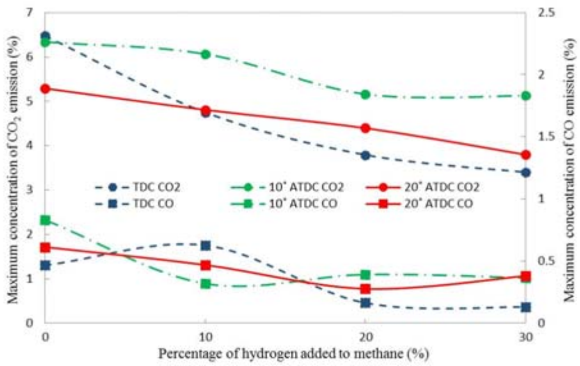

Figure-6. Maximum concentration of CO and CO_2 emission for 0% hydrogen, 10% hydrogen, 20% hydrogen and 30% hydrogen at TDC, 10˚ ATDC and 20˚ ATDC.

CONCLUSIONS

The results from the simulation study showed that the emissions from the combustion of methane hydrogen mixture is cleaner than the emissions from the combustion of 100% methane fuel. This was proven by the decreasing percentage of CO and CO_2 produced when an increasing percentage of hydrogen added. Although at some point, the emissions of CO and CO_2 were increased due to the limited analysis area which focused only under the cylinder head in the combustion chamber, but the overall effect of hydrogen addition in methane gives the positive impact on the issue of reducing the CO and CO_2 emissions. The fluctuation that occurs from the emissions of CO and CO_2 was the result from the change of temperature in the combustion chamber and due to complex combustion reaction and the incomplete combustion of fuel.

Therefore, the percentage of CO_2emissions to the environment can be reduced by implementing the hydrogen-methane mixture in internal combustion engine.

ACKNOWLEDGEMENT

The author would like to thank Ministry of Education Malaysia for supporting the research with the grant FRGS/2/2013/TK01/UKM/02/1 and GGPM-2013-093.

REFERENCES

[1] Guo L.S., Lu H.B. and Li J.D. 1999. A hydrogen injection system with solenoid valves for a four-cylinder hydrogen-fuelled engine. International Journal of Hydrogen Energy. 24(4):377-382.

[2] Wang J., Huang Z., Fang Y., Liu B., Zeng K., Miao H. and Jiang D. 2007. Combustion behaviors of a direct-injection engine operating on various fractions of natural gas–hydrogen blends. International Journal of Hydrogen Energy. 32(15):3555-3564.

[3] Das L.M., Rohit Gulati and Gupta P.K. 2000. A comparative evaluation of the performance characteristics of a spark ignition engine using hydrogen and compressed natural gas as alternative fuels. International Journal of Hydrogen Energy. 25(8):783-793.

[4] Mohammadi A., Shioji M., Nakai Y., Ishikura W. and Tabo E. 2006. Performance and combustion characteristics of a direct injection SI hydrogen engine. International Journal of Hydrogen Energy. 32(2): 296-304.

[5] Yamin J.A.A., Gupta H. N., Bansal B.B. and Srivastava O. N. 2000. Effect of combustion duration on the performance and emission characteristics of a spark ignition engine using hydrogen as a fuel. International Journal of Hydrogen Energy. 25(6):581-589.

[6] Mansor M.R.A., Nakao S., Nakagami K., Shioji M., and Kato A. 2012. Ignition characteristics of hydrogen jets in an argon-oxygen atmosphere. SAE Technical Paper2012-01-1312.

[7] Verstraeten S., Sierens R. and Verhelst S. 2004. A high speed single cylinder hydrogen fuelled internal combustion engine. FISITA World Automotive Congress 2004. 1-10.

[8] Mansor M.R.A. and Shioji M. 2012. Characterization of hydrogen jet development in an argon atmosphere. Zero-Carbon Energy Kyoto 2012. 133-140.

[9] White C.M., Steeper R.R. and Lutz A.E. 2006. The hydrogen-fueled internal combustion engine: A technical review. Internal Journal of Hydrogen Energy. 31(10):1292-1305.

[10] Morrison G.M, Kumar R., Chugh C., Puri S.K., Tuli D.K. and Malhotra R.K. 2012. Hydrogen transportation in Delhi? Investigating the hydrogen-compressed natural gas (H-CNG) option. International Journal of Hydrogen Energy. 37(1):644-654.

[11] Ma F., Wang M., Jiang L., Chen R. and Deng J. 2011. Performance and emission characteristics of a turbocharged CNG engine fueled by hydrogen-enriched CNG with high hydrogen ratio. International Journal of Hydrogen Energy. 35(12):6438-6447.

[12] Hagos F.Y., Aziz A.R.A. and Sulaiman S.A. 2014. Syngas (H_2/CO) in a spark ignition engine direct-injection engine. Part 1: Combustion, performance

and emissions comparison with CNG. International Journal of Hydrogen Energy. 39(31):17884-17895.

[13] Mohammed S.E, Baharom M.B., Aziz A.R.A. and Firmanshah. 2011. The effects of fuel-injection timing at medium injection pressure on the engine characteristics and emissions of a CNG-DI engine fueled by a small amount of hydrogen. International Journal of Hydrogen Energy. 36(18):11997-12006.

[14] Balat M. 2008. Potential importance of hydrogen as a future solution to environmental and transportation problems. International Journal of Hydrogen Energy. 33(15):4013-4029.

[15] Canakci M. 2007. An experimental study for the effects of boost pressure on the performance and exhaust emissions of a DI-HCCI gasoline engine. Fuel. 87(8):1503-1514.

[16] Mathai R., Malhotra R. K., Subramaniam K. A. and Das L. M. 2012. Comparative evaluation of performance, emission, lubricant and deposit characteristics of spark ignition engine fueled with CNG and 18% hydrogen-CNG. International Journal of Hydrogen Energy. 37(8):6893-6900.

[17] Kurniawan W.H.and Abdullah S. 2008.Numerical analysis of the combustion process in a four-stroke compressed natural gas engine with direct injection system.Journal of Mechanical Science and Technology. 22(10): 1937-1944.