MIE12-060

Influence of hydrogen on engine emissions -a review

Md. Nurun Nabi, Md. Mahabub Hasan Mousum
Department of Mechanical Engineering
Rajshahi University of Engineeringand Technology (RUET), Rajshahi
Email: nahin1234@hotmail.com; mousum_mahabub@yahoo.com

Abstract

This report collects and analyzes the experimental data and observations made in scientific journals about spark ignition and compression ignition engine emissions when using hydrogen fuel as opposed to conventional diesel, vegetable oil, biodiesel, alcohol, oxygenated and gasoline fuels. The whole analysis confined to the engine emissions from hydrogen and other fuels comparison. Dedicating attention to the most concerning emissions are carbon monoxide (CO), oxides of nitrogen (NOx), carbon dioxide (CO_2),un-burned hydrocarbon (HC) and particulate matter (PM). Over the entire observation the highest consensus was found in the sharp reduction of CO, $CO_2$and HC in emissions. Although hydrogen addition increases NOx emissions, this can be compensated by retarding the spark timing and running leaner operation, which are allowed by the faster burning velocity and broader ignition limit of hydrogenNOx can be also minimized by using exhaust gas re-circulation (EGR) in dual fuel operation. Though EGR reduces NOxemission significantly but also increases CO and HC emissions. For an optimum EGR rate all the emissions for an engine can be limited to a least quantity. The remarkable property of hydrogen fuel isless carbon content.

Key words: Emissions, Hydrogen fuel, alternative fuel, hydrocarbon engine, fuel economy, duel fuel operation.

1. Introduction

Researchers are forced to concentrate on finding renewable alternatives to conventional petroleum fuels due to the concern about environmental and depletion in petroleum resources. Clean burning nature and eventual availability from renewable sources making hydrogen to be a major energy resource of the future. Hydrogen is proving itself as the best transportation fuel of the future as it has remarkable combustion properties in the conventional internal combustion engine. Some important properties of hydrogen are given in Table 1.Hydrogen has been also recognized for its extremely high energy potential. Hydrogen has some difficulties in handling in its gaseous form. Over the past two decades, researchers are emphasized on the technology of utilizing hydrogen in its liquid form. Higher thermodynamic efficiency can be achieved from the combustion of hydrogen due to its higher flame speed when compared to conventional liquid fuels [1]. So hydrogen can also be used to enhance the combustion rate of slow burning fuels. The wider flammability limits of hydrogen results in low HC and CO emissions when it is used along with other fuels.

Table 1Fuel Properties of Hydrogen [2-6]

Properties	**Value**
Calorific value (MJ/kg)	119.81
Equivalence ratio of lean limit at 293 K, 1 atm	0.10
Flame velocity (m/s)	2.70
Density at 300K and 1 atm (kg/m^3)	0.083
Stoichiometric A/F ratio (kg/kg)	34.20
Volumetric fraction of fuel at stoichiometric A/F(%)	29.0
Molar carbon to hydrogen ratio	0.00
Laminar burning velocity (m/s)	2.90
Adiabatic flame temperature in air (K)	2318
Minimum energy required for ignition in air (MJ)	0.02
Auto ignition temperature (°C)	585

A comparison of various fuel properties of hydrogen and other fuels is presented in Table 2. Alternative fuels that desire to replace petroleum-based fuels include alcohols, liquefied petroleum gas (LPG), compressed natural gas (CNG), hydrogen, vegetable oils, bio gas, producer gas and liquefied natural gas (LNG) [7]. Among them hydrogen has the ability to be long-term renewable and less-polluting fuel. Moreover hydrogen is non-toxic, odorless and results in complete combustion. For these improved characteristics of hydrogen as an alternative fuel in internal combustion engines (ICEs) and in the development of fuel cell powered vehicles and hybrid electric vehicles (HEVs) researchers are focusing their attention on hydrogen. Using hydrogen in diesel engines as an alternative fuel is the recent concept. Hydrogen cannot be used directly in CI engine without a spark plug or glow plug. That makes hydrogen out of focus from the sole operation in diesel engines. So an alternative solution is the dual fuel operation of CI engine where diesel is used as a pilot fuel for ignition [7, 8]. Better mixing of air and hydrogen results in a complete combustion. Hydrogen enriched air systems in diesel engines enable the realization of higher brake thermal efficiency[7]. Among all fuels that can be used on SI engines Hydrogen is the most promising green alternative fuel due to its unique combustion and physicochemical properties. Fuel with these kinds of properties is helpful for improving combustion process. More over hydrogen's high burning velocity assists hydrogen engines to reach much closer to the ideal constant volume combustion which rewards improving the engine thermal efficiency. Hydrogen addition results in improving engine combustion and emissions performance is more remarkable at low load conditions than at high load conditions [9].Hydrogen can also use in spark ignition (SI) engine as a sole fuel, either by carburetion or by direct injection. As hydrogen has a flame speed five times more than that of gasoline which permits a short combustion

Table2Comparison of fuel properties [1- 5, 10-11]

Properties	Diesel	Gasoline	Jatropha oil	Hydrogen	DEE	RME
Density(kg/m^3) (25°C)	840	740	917	82	920	860-900
Calorific value (MJ/kg)	42.49	44.00	39.77	119.81	33.90	36.70
Flame velocity (m/s)	0.3	0.415	N/A	2.70	0.2339	N/A
Cetane number	45–55	N/A	40–45	N/A	>125	51
Auto ignition temp (°C)	280	257	340	585	160	N/A
Carbon residue %	0.1	N/A	0.54	N/A	0.0	N/A
Quenching gap (cm)	N/A	0.20	N/A	0.064	N/A	N/A
Octane rating	30	90–98	N/A	130	N/A	N/A
Stoichiometric A/F	14.5	14.6	N/A	34.3	N/A	12.61

duration. So the cyclic variation of hydrogen fueled engines is lower than that of gasoline-fueled engines. There is a comparable power output of a hydrogen powered S.I. engine with gasoline, thought it has some difficulties as backfire, pre-ignition and NOx emissions. It is due to the low energy density of hydrogen on volume basis. These problems can be overcome by adopting proper control of hydrogen using electronic fuel injection or induction system. Hydrogen in SI engine results in improved thermal efficiency as well as exhaust emissions [5].The commercialization of hydrogen engines in the near future is blocked by the high costs of hydrogen production and the lack of hydrogen fueling infrastructure at present [9].The technical literature reviews are indicating in favor of Hydrogen. Hydrogen is only one of many possible alternative fuels that can be derived from natural resources such as coal, oil shale and uranium or from renewable resources based on solar energy. Electrolysis of water, coal gasification-chemical decomposition of water and solar photo-electrolysis are the various commercial production process of hydrogen, although these are currently still in the laboratory stage. The development of practical and highly efficient process of hydrogen production method will end the use of hydrogen converter such as fuel cells, should lead to a dramatic reduction in cost and improvement in efficiency of hydrogen production. From the point of view of chemistry, hydrogen is unstable gas so storage is the major concern of hydrogen usage. Fuel cells are also providing safe and convenient onboard storage of hydrogen.

2. Discussions of emissions with hydrogen as fuel

In this section, emissions include CO, NOx, THC, CO_2 and particulate matter with hydrogen as fuel are discussed. The discussions are limited to compression ignition (CI) engine and spark ignition (SI).

2.1Effect of hydrogen addition on CO emissions

Korakianitis et al.[2] studied the water-in-biodiesel emulsions as pilot fuel along with hydrogen as secondary fuel in a four-stroke 1.5L single-cylinder CI engine during a dual fuel operation. For all tests, the engine was run at 750 rpm and 1000 rpm. The biodiesel used in this case was rapeseed methyl ester (RME), while it was emulsified with 5% and 10% distilled water, 5% and 10% of a total fixed volume was distilled water and 95% and 90% were RME.During this dual fuel operation with the increasing hydrogen addition at both speeds for all pilot fuels CO emissions were similar to normal CI engine operation. Authors observed CO emissionsweredecreased with the increasing equivalence ratio during hydrogen-diesel operation. In the combustion reaction the addition of hydrogen reduced the carbon content and increased the temperature. Along with that variation of oxygen concentration with the increasing equivalence ratio influenced the combustion to be completed. Roy et al. [12] conducted experimentsby usinghydrogen-rich coke oven gas and ignited by a pilot amount of diesel fuelin a four-stroke, single cylinder, water cooled, supercharged,dual-fuel engine.An experiment were carried out at a constant pilot injection pressure and pilot quantity for different fuel-air equivalence ratios and at various injection timings with and without exhaust gas recirculation (EGR).It was observed that the CO emissions were increased with the increasing EGR rate. Authors found lower CO emissions at advanced injection timings. Bose et al. [13] observed reduced CO emissions with various EGR rates than the neat diesel operation at high load. The experiment was carried out by using a four stroke, water cooled, single cylinder, vertical diesel engine running at a rated power of 5.2 kW and at a rated speed of 1500 rpm. Authors developed a timed manifold induction system to deliver hydrogen in to the intake manifold which was electronically controlled. Minimum CO emissions were observed for hydrogen-diesel operation without using EGR. Combined EGR and hydrogen operation reduced CO emissions compared to neat diesel operation. Saravanan et al. [4] investigated the mixing of hydrogen-diesel, and hydrogen-DEE (diethyl ether) in a single cylinder water-cooled DI diesel engine having a rated power of 3.7 kW that runs at a constant speed of 1500 rpm. Authors observed higher CO emissions at part load condition in hydrogen-DEE operation than the CO emissions in both hydrogen-diesel operation and in base diesel operation. As a result hydrogen-diesel operation was more advantageous than net diesel and hydrogen-DEE operation, due to lower CO emissions in part load condition. The higher CO emissions during hydrogen-DEE operation were due to the lower combustion temperature. But, at high load condition the hydrogen-DEE operation had lower CO emissions than other operations. In hydrogen-DEE operation the engine was not able run beyond 75% load due to severe knocking.Xu et al. [14] carried out an investigation with an electronic-controlled single cylinder port fuel injection diesel engine, modified to be a CNG (Compressed Natural Gas) engine having a rated power of 10.3 kW that runs at a constant speed of 2000 rpm, which was fueled with pure natural gas and natural gas–hydrogen blends. It was reported that with the increase in hydrogen fraction in the blends resultedinthe decreased CO emissions. However, for lean fuel–air mixtures CO emissions were slightly decreased with the increasing hydrogen fraction. This was associated with hydrogen's ability to strengthen the combustion reaction. Kumar et al. [1] used jatropha oil (vegetable oil) as pilot fueland hydrogen as secondary fuel in a single cylinder water-cooled direct-injection diesel engine designed to develop a power output of 3.7 kW.The engine was tested at1500 rpm under variable load conditions.Authors reported a significant reduction in CO emissions in this dual fuel operation as jatropha oil is an oxygenated fuel which provides additional oxygen to the combustion reaction. The additional fuel oxygen influenced the formation of CO_2 rather than CO emissions. Ji et al. [9] observed the effect of hydrogen addition on emission characteristics of a prototype in-line, spark-ignited (SI) gasoline engine under various loads and lean conditions. The HHGE (Hybrid Hydrogen Gasoline Engine)was operated at a constant engine speed of 1400 rpm and two Hydrogen volume fractions in the total intake of 0% and 3% were achieved through adjusting the hydrogen injection duration according to the air flow rate. Authors found decreased CO emissions in SI engine operation. Similar results (reduced CO emissions) were observed at high loads again due to better fuel energy flow and mixing of air-gasoline. Kornbluth et al. [15] conducted an experiment by using hydrogen-landfill gas (60% CH4 and 40% CO_2) fuel in a naturally aspirated spark-ignition 0.745 L, two-cylinder, liquid-cooled, port fuel-injected, KawasakiD791 DFI engine. Here LFG and hydrogen mixtures were fumigated into the intake port. Authors experienced with the decreased CO emissions using hydrogen-landfill gas fuel operation than the neat landfill gas fuel operation with the decreasing equivalence ratio. Wang et al. [16] concluded the similar result as Kornbluth et al. [15] by using a hydrogen-enriched SI ethanol engine under idle and stoichiometric conditions. The engine was modified into 1.6 L SI engine equipped with a hydrogen port-injection system. Due to less carbon content in the hydrogen-ethanol mixture, authors reported the reduced CO emissions at the beginning of combustion operation. However, authors observed increased CO emissions when the addition of hydrogen reached over 4%. The increase was attributed to the fact of fast combustion of hydrogen that could consume more adjacent air to form some lean oxygen areas where the increased CO emissions were produced. The oxygen concentration in ethanol also results in better fuel oxidation realizing increasedCO_2.An experimental investigation was carried out by Ji et al. [17] conducted experiment on a 1.6 L, port fuel injection, four-cylinder, gasoline engine. Authors foundhigherCO emissions with the increasing hydrogen addition at about stoichiometric conditions.Authors also reportedthat CO emissions decreased with hydrogen addition at lean condition.

2.2 Effect of hydrogen addition on NOx emissions

Kumar et al. [1] found higher NOx emissions with jatropha oil (vegetable oil) and hydrogen dual fuel operation compared to neat jatropha oil operation at maximum power output condition.The increase in NOx emissions with the hydrogen addition at high loads was associated with the increased combustion temperature.On the other hand,little variations in NOx emissions were observed at low power output condition.In dual fuel operation, the peak pressure and maximum rate of pressure rise were higher when hydrogen was introduced. The peak pressure and maximum rate of pressure rise were reduced at low loads, using both diesel and jatropha oil when hydrogen was inducted. Korakianitis et al.[2] studied the emission characteristics of water-in-biodiesel emulsions as pilot fuel along with hydrogen as secondary fuel in a CI engine. Authors reported lower NOx emissions for emulsified pilot fuels when compared with the normal CI engine operation withrapeseed methyl ester (RME) (except at maximum load) at an engine speed of 750 rpm. Introducing water results in the cooling effect which leads to reducedcombustion temperatures and pressure rise rates.Compared to 5% emulsified water-RME pilot fuel combustion, the 10% emulsified water-RME pilot fuel produced lower NOx emissions. Roy et al. [12] investigated the engine emissions of a supercharged dual-fuel engine, fueled with hydrogen-rich coke oven gas and ignited by a pilot amount of diesel fuel. The engine used for this experiment was a four-stroke, single cylinder water cooled engine. Authors observed increased NOx emissions with the increase in injection advance. Authors reported lower NOx emissions (30% reduction) with 40% EGR. Saravanan et al. [4] conducted with hydrogen-DEE, hydrogen-diesel and neat diesel fuel. In hydrogen-DEE operation the NOx emissions were reported to be lower than for both the hydrogen-diesel and base diesel operations. For hydrogen-DEE operation, the NOx emissions were lower due to the lower peak combustion temperature. Authors reported lower inlet charge temperature which resulted in lower peak combustion temperature as the test engine was water cooled diesel engine. Xu et al. [14] also reported higher NOx emissions with the increasing hydrogen fraction in the blends. NOx emissions increased rapidly for leaning out the engine and then NOx emissions decreased gradually to a relatively low level after reaching to a peak value. However, at a constant excess air ratio increased NOx emissions were found with the increasing hydrogen addition. The higher NOx emission was due to higher combustion temperature caused by the hydrogen addition. Lambe et al. [18] studied the emission characteristics of diesel as pilot fuel along with hydrogen as secondary fuel in an open chamber, normally aspirated, direct injection diesel engine having a rated power of 6 kW that runs at a constant speed of 2000 rpm.Authors observed a reduction in NOx emission for hydrogen-diesel dual fuel operation than the neat diesel operation at light loads. The lower NOx emissions was due to more uniform temperature distribution obtained with the gas-air mixture reducing the high temperature region around the diesel flame. Bose et al. [13] conducted an experiment by using diesel and hydrogen-enriched air blend in a four stroke, water cooled, single cylinder, vertical diesel engine. From the analysis of exhaust emission characteristic, it was reported that higher NOx emissions were observed for hydrogen-diesel operation than the neat diesel operation at 80% load. Again reduced NOx emissions were found with the EGR technique in hydrogen-diesel operation when compared with the neat diesel operation. Saravanan et al [19] conducted an investigation by using a naturally aspirated stationary DI diesel engine having a rated output of 3.7 kW at 1500 rpm. The engine was modified to operate with hydrogen by positioning the injector on the cylinder head for port injection and intake manifold for manifold injection.Authors observed that at no load NOx emissions in diesel operation were more than the hydrogen-dieselport injection and manifold injection operation. The reduction of NOx emissions in hydrogen-diesel operation was influenced by the reduced peak combustion temperature, which was as a result of hydrogen operation with very lean mixtures. However, at75% load, NOx was observed to be higher in port-injected hydrogen engine compared to diesel and manifold injection. Authors reported that NOx emission increases by 6% at 75% load and 3% at full load in port injection compared to manifold injection. It wasobserved that the peak heat release rate inthe case of port injection was higher than that of manifold injection. It was anticipated that due to higher peakheat release; the peak combustion temperature may be higher,which may result in increased NOx emissions. Authors noted that temperature was the main factor for the formation of NOx compared to the availability of oxygen concentration. Mathur et al. [20] carried out an experiment for controlling the exhaust emission parameters of all small horse power (4 kW rating) hydrogen fueled diesel engine using various diluents mixed with the inducted charge. Hydrogen fuel from a high pressure cylinder was inducted through an intake retrofit. Authors used helium, nitrogen and wateras diluents. Higher NOx emissions were obtained for hydrogen fueling engine. Usingdiluent helium, NOx emissions were limited to lower levels of increment. On the other hand, nitrogen as diluent increases NOx emissions slightly. But, the higher concentrations of nitrogen as diluents decelerate the increment rate. Water as diluent reduced NOx emissions to baseline values. Among all the diluents water was the most appropriate, because of its practicability and economy. Ji et al. [9] observed that the NOx emissions were increased with the cylinder temperature during the combustion in both the original engine and the HHGE. And it was due to reduced combustion duration and increased fuel energy flow rate. Furthermore, the NOx emissions were increased with hydrogen addition because of the increased cylinder temperature caused by the faster combustion of the hydrogen-gasoline mixture than the pure gasoline. Kornbluth et al. [15] reported that NOx emissions were increased with the addition of hydrogen at a constant equivalence ratio. Hydrogen's higher specific energy density was ascribable to higher combustion temperature, which resulting in increased NOx emissions. Increasing hydrogen from 0-50% resulted in lean operation led to decrease in NOx emissions. Wang et al. [16] observed that NOx emissions were increased with increasing hydrogen addition. High specific heat of hydrogen was the reason to its high flame speed and combustion temperature. This high combustion temperature was responsible for influencing nitrogen in air to form NOx by reacting with oxidizer. It was reported that the NOx emissions were continuously increased with the increasing hydrogen blending ratio at idle and stoichiometric conditions. Ji et al. [17] also reported increased NOx emissions.

2.3 Effect of hydrogen addition on CO_2 emissions

Saravanan et al. [4] observed thedeterioration of CO_2 emissions with the increasing load in hydrogen-diesel operation. The reduction of CO_2 emissions was comparatively higher than the neat diesel operation. And it was due to the absence of carbon in hydrogen and better combustion properties of hydrogen. Moreover, the CO_2emissions for hydrogen-DEE operation were less than the CO_2 emissions for hydrogen-diesel operation and base diesel operation. Korakianitis et al. [2]observed that there was a significant reduction in CO_2 emissions with increasing load during dual-fuel operation of biodiesel and hydrogen. The CO_2 emissions were influencedby the amount of carbon supplied into the engine by the injected fuel. During the hydrogen-diesel dual fuel operation more hydrogen (which contains no carbon) was being used for producing similar levels of power as in normal CI engine operation. Xu et al. [14] tested an electronic-controlled single-cylinder engine fueled with pure natural gas and natural gas-hydrogen blends to evaluate the exhaust emissions. The increased hydrogen fraction in the blends was responsible for the deterioration in CO_2 emissions. The CO_2 emissions were also influenced by the carbon content of hydrogen. When fuel–air mixtures were gradually leaned out, CO_2 emissions decreased to a relatively lower lever. Lambe et al. [18] reported that the CO_2 in hydrogen-diesel operation was less than neat diesel operation. It was due to hydrogen has less carbon content than diesel. Thus a hydrogen-fueled diesel engine offers a viable option to reduce carbon dioxide (a greenhouse gas) emissions inthe engine exhaust. Saravanan et al. [3] and Bose et al. [13] also reported about the decreased CO_2 emissions with the increasing load in diesel and hydrogen-enriched air dual fuel operation. The decrease in CO_2 emissions were pointed out as the less presence of carbon during the combustion process. But CO_2 emissions increases when the engine was operated with EGR along with hydrogen addition. Bose et al. reported that the CO_2 emissions were increased with the increasing percentage of EGR. It was due to more CO_2 was re-circulated in the engine cylinder and reduced the supply of oxygen for combustion. Masood et al. [21] conducted an experimental investigation for analyzing the exhaust species when the hydrogen is burnt with diesel fuel. The investigation was carried out by using hydrogen–diesel dual fuel engine under constant speed, variable compression ratios and variable load conditions. The amount of primary fuel, i.e. diesel was varied and hydrogen was substituted at each load. Authors observed that CO_2 emissions were decreased at high temperature during hydrogen-diesel dual fuel operation. It was due to dissociation of CO_2into CO at high temperature. CO_2 was the major product of lean and rich mixture. During the experiment, they found variation in CO_2 emissions, which was due to different load conditions. Ji et al. [9] observed that in HHGE, the gasoline flow rate was reduced after the addition of hydrogen, for which there was an excess air ratio inside the engine cylinder. The carbonless combustion results in lower CO_2 emission.Another experimental study was carried out by Ji et al. [17] on a SI engine. Authors found that CO_2 emissions were effectively reduced with the increasing hydrogen addition. It was due to the fact of carbonless hydrogen fuel. The increase in hydrogen addition results in decrease in gasoline introduction. Thus, the carbonless fuel reduced CO_2 emissions.

2.4 Effect of hydrogen addition on unburnt HC emissions

Kumar et al. [1] reported lower HC emissions with hydrogen. As hydrogen has no carbon in its molecule, thus, combustion of hydrogen increased the cylinder gas temperature and pressure, which resulted in the complete burning of the jatropha oil hydrocarbon fuel eventually led to the reduction of HC emissionswith the increasing brake thermal efficiency. Saravanan et al. [4] investigated the emission characteristics of hydrogen-diesel and hydrogen-DEE (diethyl ether) in a modified diesel engine. Authors observed higher HC emissions for hydrogen-DEE operation compared to hydrogen-diesel operation and neat diesel operation at all loading conditions. The higher HC emissions were due to lack of oxygen during diffusion combustion stage. Ji et al. [9] reported lower HC emissions at higher load.Wang et al. [16] discussed about HC emissions by using a hydrogen-enriched SI ethanol engine under idle and stoichiometric conditions. The ethanol was injected into the intake ports using the original engine gasoline injection system. Authors reported decreased HC emissions with increased hydrogen addition. The lower HC emissions were due to the fact of the lower carbon content and reduced ethanol flow rate with the increasing hydrogen addition.Slightly increased HC emissions were reported; when H_2 was over 5.49%.Jiet al. [5]observed backfire and higher HC emissions with more than 14.44% hydrogen addition. This was associated with the drop of total energy in the flow into the cylinder. The lower energy was responsible for lower combustion temperature. Authors reported that less than 14.44% hydrogen addition, the THC emission was less than that of no hydrogen operation. An experimental investigation was carried out by Hu et al. [22] to study the influence of hydrogen addition and EGR rates on the emissions of a spark-ignition engine.Authors observed little variation in HC emissions at low EGR rate. The increase in HC emissionwas remarkable when EGR rate was over a certain value. The bulk quenching at low and large cycle-by-cycle variations were the factors to this behavior when EGR rate was over the value. However, HC decreased with the increasing hydrogen fraction in the blends.Increasing of hydrogen content actually decreased the unburned fuel from natural gas. Authors also reported the reason for the lower HC emission that the quenching distance of the mixture was decreased with the increasing hydrogen fraction in the fuel blend, and this decreased the unburned fuel in the quenching layer on the combustion chamber surface, enabling the flame to propagate into the top-land crevice and decreased HC from the crevice. Also, HC post-flame oxidation was promoted due to the increased combustion temperature as hydrogen addition. Authors concluded that the factors discussed abovewere responsible for reduced the exhaust HC concentration with the increasing hydrogen fraction. Ji et al. [17]found that HC emissions were gradually decreased with the increasing excess air ratio and hydrogen addition. It was reported that due to the formation of OH radical that was accelerated by hydrogen addition. So,hydrogen-gasoline mixture was more fully burnt and emitted less HC emissions than gasoline, due to the improved chain reaction. The shorter quenching distance of hydrogen than the gasoline was another possible reason for the reduced HC emissions.

2.5 Effect of hydrogen addition on particulate matter (PM) and smoke emissions

Saravanan et al. [7] studied the emissions characteristics of the hydrogen-enriched engine. Authors found that as hydrogen is a carbonless fuel, so during the hydrogen enriched combustion of diesel, lower particulate emissions were experienced.Kumaret al.[1] found that in dual fuel operation with jatropha oil and diesel as pilot fuels, there was a significant reduction in smoke level at all rates of hydrogen admission. Since smoke is a part of particulate matter, so the reduction in smoke emission results in particulate matter emission. The introduction of hydrogen reduced the injected fuel and minimized the smoke level. It was observed that neat jatropha oil operation showed a good reduction in smoke and PM level compared to neat diesel operation at all loads.Zhao et al. [23] analyzed PM emissions of a direct injection spark ignition engine by using hydrogen and gasoline mixtures.Authors observed that blending of hydrogen reduced the PM emission level more significantly at low load than at high load.

3. Conclusions

This paper reports on the role of hydrogen fuels on diesel, vegetable oil, biodiesel, alcohol, oxygenated fuels and gasoline emissions. The results of the different research papers were analyzed and can be summarized as follows:

1. Higher NOx emissions were experienced for most of the dual fuel operations usinghydrogen as fuel. Compared with other fuels, hydrogen increased NOx emissions in most of the SI engine operations. The most effective way of reducing NOx emission is EGR. However, EGR increased other emissions. Water enriched pilot fuel is also an effective way of reducing NOx.

2. CO emissions showed similar variation with hydrogen and other fuels. Lower CO emissions were resulted in using hydrogen as fuel. However, higher CO emissions were observed with the load. Also higher CO emissions were experienced with the EGR using hydrogen-diesel operation. Compared neat diesel operation, hydrogen-diesel operation resulted in lower CO emissions.

3. Lower $CO_2$was observed with hydrogen fuel. CO_2varies during dual fuel operation and SI engine operation with various fuels.

4. HC emissions decreased with hydrogen addition at high load condition forSI engine operation and most of the dual combustion using hydrogen as fuel. The higher rate of EGR increases HC emissions.

5. The formation of PM emission is associated with the incomplete combustion of hydrocarbon fuels. The PM emissions also result from burning of lubricating oil.

Based on the discussions and analyses, hydrogen engines can be treated as environmental friendly engine for the fuel and engine researchers.

References

[1]Kumar MS, Ramesh A,Nagalingam B, “Use of hydrogen to enhance the performance of a vegetable oil fuelled compression ignition engine”. Hydrogen Energy 28, pp 1143 – 1154, (2003).

[2]Korakianiti T, Namasivayam AM, Crookes RJ, "Hydrogen dual-fuelling of compression ignition engines with emulsified biodiesel as pilot fuel". Hydrogen Energy 35, pp13329 -13344, (2010).

[3]Saravanan N,Nagarajan G, Dhanasekaran C, Kalaiselvan KM, "Experimental investigation of hydrogen port fuel injection in DI diesel engine". Hydrogen Energy 32, pp 4071 – 4080, (2007).

[4]Saravanan N, Nagarajan G, Sanjay G, Dhanasekaran C, Kalaiselvan KM, "Combustion analysis on a DI diesel engine with hydrogen in dual fuel mode". Fuel 87, pp3591–3599, (2008).

[5]JiChangwei, Wang Shuofeng. "Effect of hydrogen addition on the idle performance of a spark ignited gasoline engine at stoichiometric condition". Hydrogen Energy 34, pp 3546–3556, (2009).

[6]Avadhanula VK, Lin CS, Witmer D, Schmid J, Kandulapati P, "Experimental Study of the Performance of a Stationary Diesel Engine Generator with Hydrogen Supplementation". Energy Fuels 23, pp 5062–5072, (2009).

[7]Saravanan N, Nagarajan G, "An experimentalinvestigation of hydrogen-enriched air induction in a diesel engine system". Hydrogen Energy 33, pp1769 – 1775, (2008).

[8]Saravanan N, Nagarajan G, "An experimental investigation on performance and emissions study with port injection using diesel as an ignition source for different EGR flow rates". Hydrogen Energy 33, pp4456 – 4462, (2008).

[9]JiChangwei, Wang Shuofeng and Zhang Bo, "Combustion and emissions characteristics of a hybrid hydrogen gasoline engine under various loads and lean conditions". Hydrogen energy 35, pp 5714-5722, (2010).

[10]Das LM, "Exhaust emission characterization of hydrogen operated engine system; nature of pollutants and their control techniques". Hydrogen Energy 16(11), pp. 765-775, (1991).

[11]Hoffmann P, "Tomorrow's energy hydrogen, fuel cells, and the prospects for a cleaner planet". (2001), ISBN 0-262-08295-0.

[12]Roy MM, Tomita E, Kawahara N,Yuji Harada, Atsushi Sakane, "Performance and emissions of a supercharged dual-fuel engine fueled by hydrogen-rich coke oven gas".Hydrogen Energy 34, pp9628 – 9638, (2009).

[13]Bose PK, Maji D, "An experimental investigation on engine performance and emissions of a single cylinder diesel engine using hydrogen as inducted fuel and diesel as injected fuel with exhaust gas recirculation". Hydrogen energy 34, pp4847 – 4854, (2009).

[14]XuJian, Zhang Xin, Liu J, Fan Longfei, "Experimental study of a single-cylinder engine fueled with natural gas–hydrogen mixtures". Hydrogen energy 35, pp 2909 – 2914, (2010).

[15]Kornbluth K, Greenwood J, McCaffrey Z, Vernon D, Erickson P, "Extension of the lean limit through hydrogen enrichment of a LFG-fueled spark-ignition engine and emissions reduction". Hydrogen energy 35, pp 1412 –1419, (2010).

[16]Wang Shuofeng, JiChangwei and Zhang Bo, "Effect of hydrogen addition on combustion and emissions performance of a spark-ignited ethanol engine at idle and stoichiometric conditions". Hydrogen energy 35, pp9205-9213, (2010).

[17]JiChangwei, Wang Shuofeng. "Effect of hydrogen addition on combustion and emissions performance of aspark ignition gasoline engine at lean conditions".Hydrogen energy 34, pp 7823–7834, (2009).

[18]LambeSMand Watson HC, "Low polluting, energy efficient hydrogen engine". Hydrogen Energy, 17(7), pp 513-525, (1992).

[19]Saravanan N, Nagarajan G, "Experimental investigation in optimizing the hydrogen fuel on a hydrogen diesel dual-fuel engine". Energy & Fuels 23, pp2646–2657, (2009),

[20]Mathur HB, Das LMandPatro TN, "Effects ofcharge diluents on the emission characteristics of a hydrogen fueled diesel engine".HydrogenEnergy, vol.17. No.8

[21]Masood M, Ishrat MM, "Computer simulation of hydrogen–diesel dual fuel exhausts gas emissions with experimental verification". Fuel 87, pp1372–1378, (2008).

[22]HuErjiang,HuangZ,Liu Bing, Zheng J, GuXiaolei, and Huang Bin, "Experimental investigation on performance and emissions of a spark-ignition engine fuelled with natural gas–hydrogen blends combined with EGR". Hydrogen energy 34, pp528–539, (2009).

[23]Zhao H, Stone R, Zhou L, "Analysis of the particulate emissions and combustion performance of a direct injection spark ignition engine using hydrogen and gasoline mixtures". Hydrogen energy 35, pp4676-4686, (2010).