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Use of Hydrogen-Methane Blends in Internal Combustion Engines

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Additional information is available at the end of the chapter

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1. Introduction

In today's modern world, where new technologies are continually being introduced, transportation energy use is increasing rapidly. Fossil fuel, particularly petroleum fuel, is the major contributor to energy production[1]. Fossil fuel consumption is steadily rising as a result of population growth in addition to improvements in the standard of living. It can be seen from Figure 1 that the world's population has been increasing steadily over the last 5 decades, and this trend is expected to continue [2]. As a result, total energy consumption has grown by about 36% over the last 15 years [3]. Energy consumption is expected to increase further in the future, as the world's population is expected to grow by 2 billion people in the next 30 years [2]. These energy trends can be seen in Figure 2. Increased energy demand requires increased fuel production, thus draining current fossil fuel reserve levels at a faster rate. In addition, about 60% of the world's current oil reserves are in regions that are in frequent political turmoil [3]. This has resulted in fluctuating oil prices and supply disruptions.

Rapidly depleting reserves of petroleum and decreasing air quality raise questions about the future. As world awareness about environmental protection increases so too does the search for alternatives to petroleum fuels [1].

Alternative fuels such as CNG, HCNG, LPG, LNG, bio-diesel, biogas, hydrogen, ethanol, methanol, di-methyl ether, producer gas, and P-series have been tried worldwide. The use of hydrogen as a future fuel for internal combustion (IC) engines is also being considered. However, several obstacles have to be overcome before the commercialization of hydrogen as an IC engine fuel for the automotive sector. Hydrogen and CNG blends (HCNG) may be considered as an automotive fuel without requiring any major modification in the existing CNG engine and infrastructure [4].

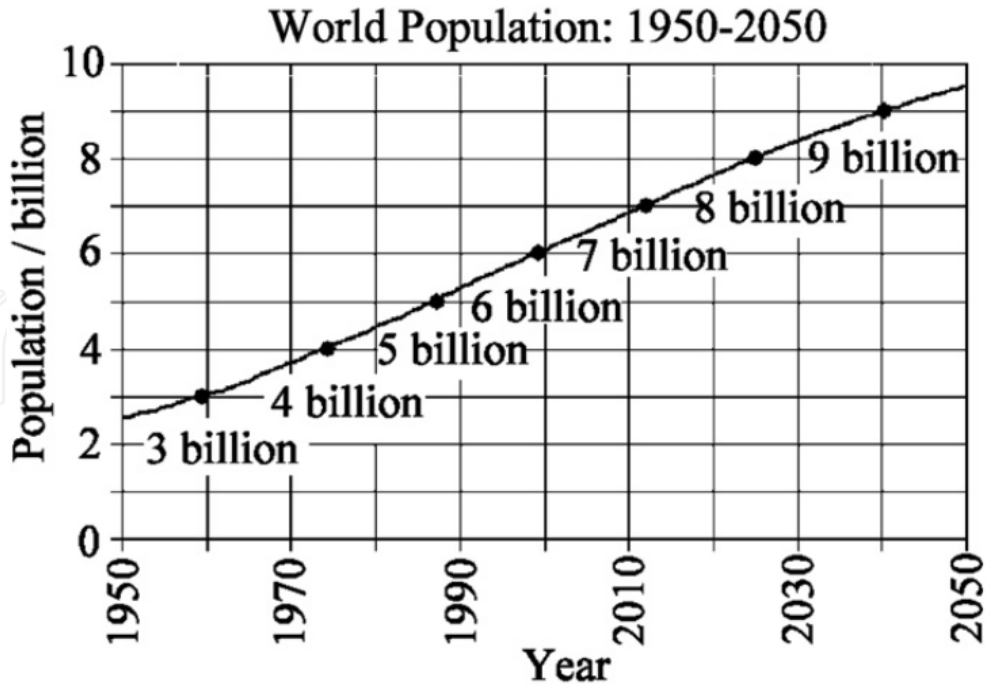


Figure 1. World population 1950-2050 [2].

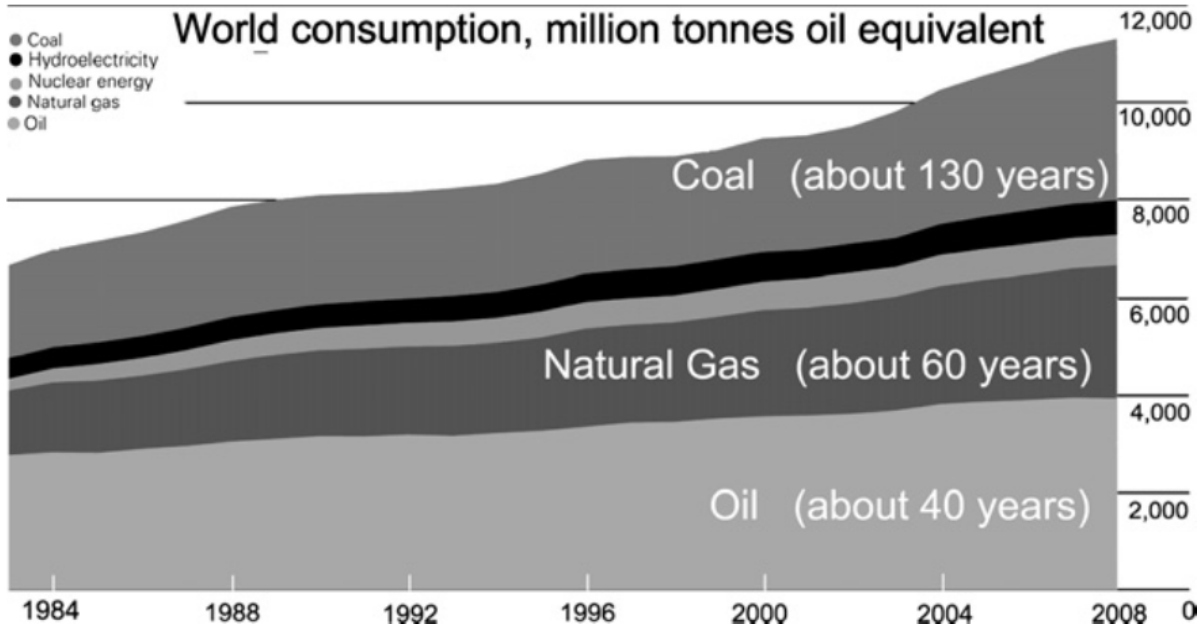


Figure 2. Fossil fuel consumption from 1983 to 2008 with approximate current reserves-to-production ratios in remaining years [3].

Alternative fuels are derived from resources other than petroleum. The benefit of these fuels is that they emit less air pollutants compared to gasoline and most of them are more economically viable compared to oil and they are renewable [5]. Figure 3 shows the percentages of alternative fuels used according to total automotive fuel consumption in the world as a futuristic view.

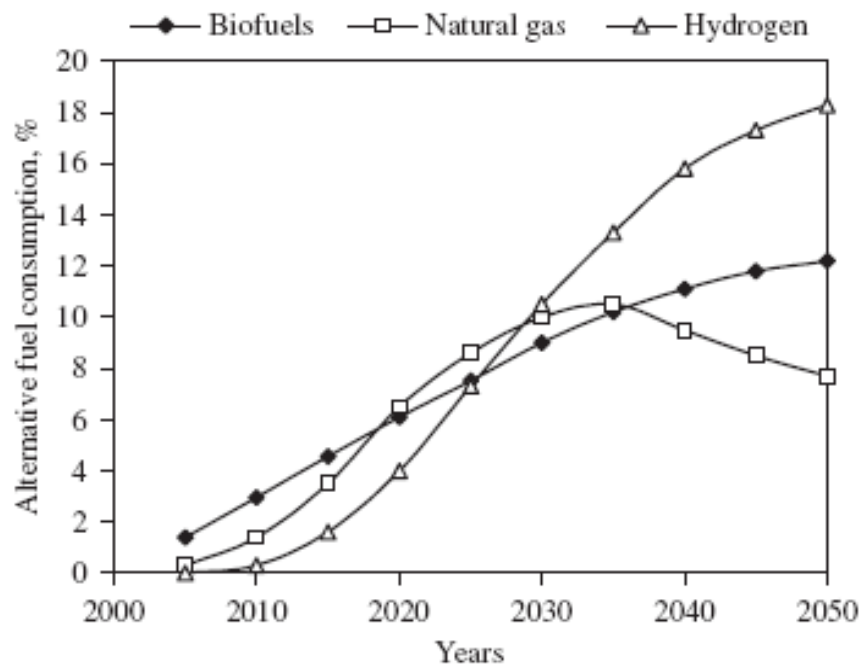


Figure 3. Percentages of alternative fuels compared to total automotive fuel consumption in the world [6]

2. Hydrogen specifications

Hydrogen is acknowledged to offer great potential as an energy carrier for transport applications. A number of technologies can use hydrogen as an energy carrier, with the internal combustion engine being the most mature technology [7]. Currently, 96% of hydrogen is made from fossil fuels. Based on 2004 data, in the United States 90% is made from natural gas, with an efficiency of 72%. Only 4% of hydrogen is made from water via electrolysis. Currently, the vast majority of electricity comes from fossil fuels in plants that are 30% efficient and from electrolysis which means that electricity is run through water to separate the hydrogen and oxygen atoms. Using renewable energy is much more effective than using fossil fuel to produce hydrogen. Current wind turbines perform at 30-40% efficiency, producing hydrogen at an overall efficiency rate of 25%. The best solar cells available have an efficiency rate of 10%, leading to an overall efficiency rate of 7%. Algae can be used to produce hydrogen at an efficiency rate of about 0.1% (see Figure 4)[8].

The use of hydrogen as an automotive fuel appears to promise a significant improvement in the performance of spark-ignition engines [9]. The self-ignition temperature of the hydrogen/air mixture is greater than that of other fuels and, therefore, hydrogen produces an antiknock quality of fuel. The high ignition temperature and low flame luminosity of hydrogen makes it a safer fuel than others, it is also non-toxic. Hydrogen is characterized by having the highest energy-mass coefficient of all chemical fuels and in terms of mass energy consumption it exceeds conventional gasoline fuel by about three times, and alcohol by five to six times [10]. Therefore, the results clearly establish that hydrogen fuel can increase the effective efficiency of an engine and reduce specific fuel consumption. A small amount of hydrogen 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 gasoline/air mixture. The resulting ultra lean combustion produces a low flame temperature and leads directly to lower heat transfer to the walls, higher engine efficiency and lower NO_x exhaust emissions [11–13].

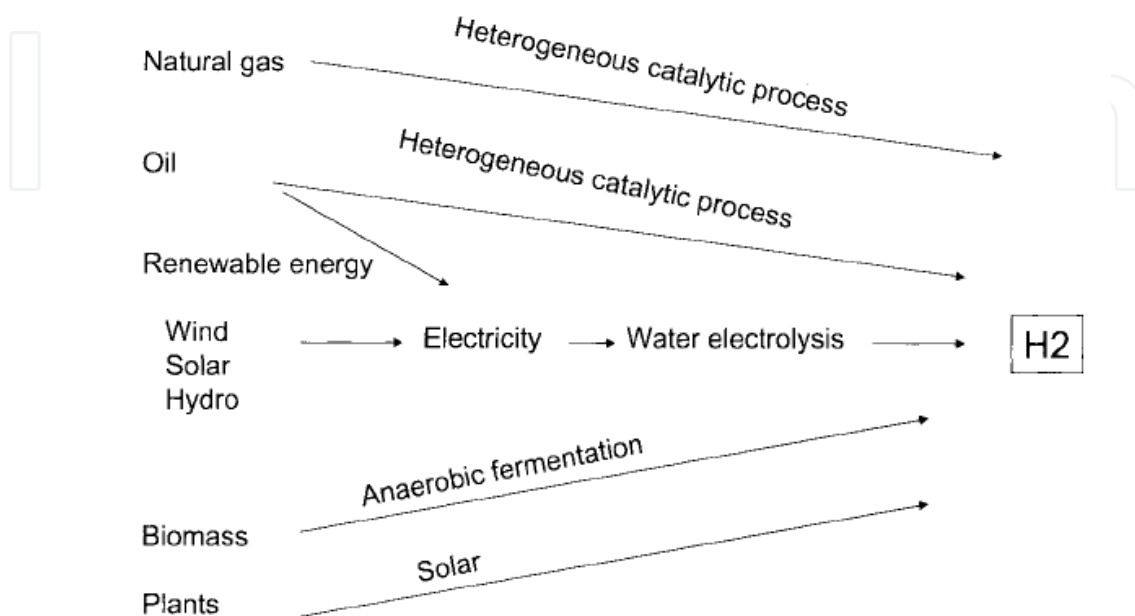


Figure 4. Various processes for the production of hydrogen[8]

The burning velocity of hydrogen/air mixture is about six times higher than that of gasoline/air mixtures. As the burning velocity rises, the actual indicator diagram is nearer to the ideal diagram and a higher thermodynamic efficiency is achieved [14,15]. Figure 5 plots the laminar burning velocities against the equivalence ratio for hydrogen–air mixtures at normal pressure and temperature (NTP)[7]. The solid symbols in Figure 5 denote stretch-free burning velocities (or rather, burning velocities that were corrected to account for the effects of the flame stretch rate), as measured by Taylor [16], Vagelopoulos et al. [17], Kwon and Faeth [18] and Verhelst et al. [19]. The empty symbols denote other measurements that did not take stretch rate effects into account, as reported by Liu and MacFarlane [20], Milton and Keck [21], Iijima and Takeno [22] and Koroll et al. [23]. These experiments result in consistently higher burning velocities, with the difference increasing for leaner mixtures.

Hydrogen is a clean fuel with no carbon emissions; the combustion of hydrogen produces only water and a reduced amount of nitrogen oxides. Conversely, combustion products from fossil fuels, such as CO, CO₂, nitrogen oxides, or other air pollutants, cause health and environmental problems. Hydrogen will help reduce CO₂ emissions as soon as it can be produced in a clean way either from fossil fuels, in combination with processes involving CO₂ capture and storage technologies, or from renewable energy. These features make hydrogen a potentially excellent fuel to meet the ever increasingly stringent environmental controls regarding exhaust emissions from combustion devices, including the reduction of green house gas emissions [24–27].

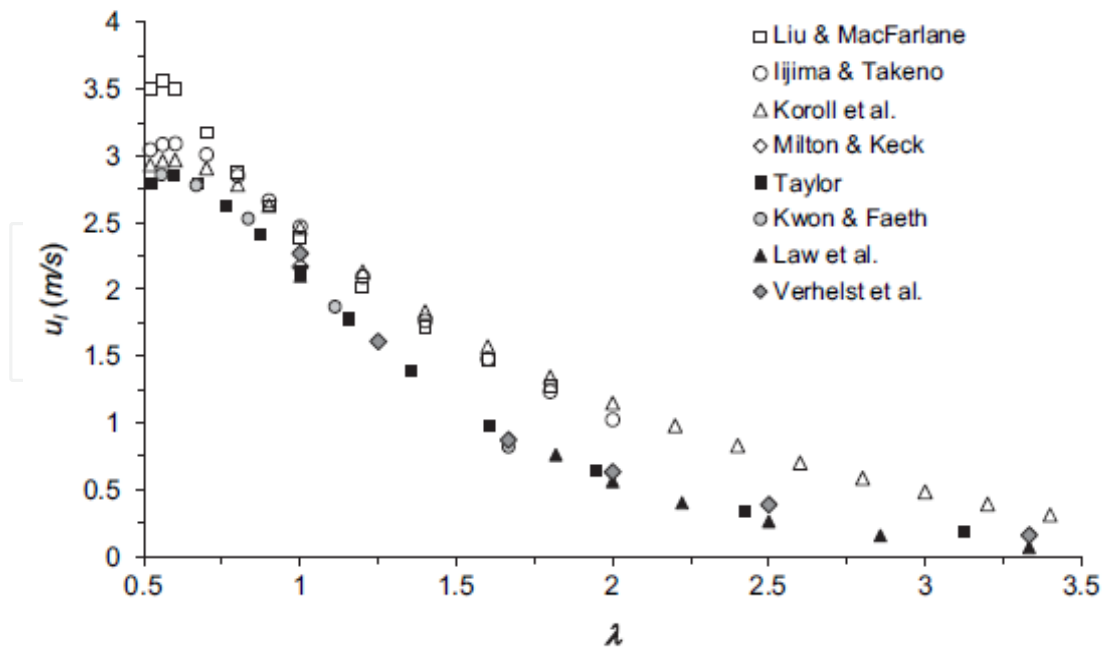


Figure 5. Laminar burning velocities plotted against air-to-fuel equivalence ratio, for NTP hydrogen–air flames[7]. The experimentally derived correlations are from Liu and MacFarlane [20], Milton and Keck [21], Iijima and Takeno [22] and Koroll et al. [23]. Other experimental data are from Taylor [16], Vagelopoulos et al. [17], Kwon and Faeth [18] and Verhelst et al. [19].

3. Methane specifications

Natural gas (CNG) is considered as an alternative vehicle fuel because of its economical and environmental advantages [28]. CNG, which is a clean fuel with methane as its major component, is considered to be one of the most favorable fuels for engines, and the utilization of CNG has been realized in spark-ignition engines. However, due to the slow burning velocity of CNG and its poor lean-burn capability, the CNG spark-ignition engine still has some disadvantages like low thermal efficiency, large cycle-by-cycle variation, and poor lean-burn capability, and these decrease engine power output and increase fuel consumption [29]. The advantages of CNG compared to petrol are as follows: unique combustion and suitable mixture formation; due to the high octane number of CNG, the engine operates smoothly with high compression ratios without knocking; CNG with lean burning quality leads to the lowering of exhaust emissions and fuel operating cost; CNG has a lower flame speed; and engine durability is very high. CNG is produced from gas wells or related to crude oil production. CNG is made up primarily of methane (CH_4) but frequently contains trace amounts of ethane, propane, nitrogen, helium, carbon dioxide, hydrogen sulfide, and water vapor. Methane is the principal component of natural gas [30].

CNG has many other advantages as well. It has a high octane number of 130, which enables an engine to operate with little knocking at a high compression ratio. In addition, gasoline and diesel engines can be easily converted into CNG engines without major structural changes [31]. Not only does the CNG engine have good thermal efficiency and high power,

but its combustion range is also broad. This is an advantage when striving for lean combustion resulting in low fuel consumption and less NO_x production [32]. The CNG engine also yields very low levels of PM emissions when compared with other conventional engines. These facts are supported by an experimental study performed to explore the combustion and emission characteristics of both gasoline and CNG fuels using a converted spark-ignition engine [33]. In light of these advantages, the number of CNG vehicles is continuously growing, and old vehicles are being converted into CNG vehicles through engine modifications [34].

4. Hydrogen-methane mixtures for internal combustion engines

Traditionally, to improve the lean-burn capability and flame burning velocity of natural gas engines under lean-burn conditions, an increase in flow intensity is introduced in the cylinder, and this measure always increases the heat loss to the cylinder wall and increases the combustion temperature as well as the NO_x emission [35]. One effective method to solve the problem of the slow burning velocity of natural gas is to mix natural gas with fuel that possesses fast burning velocity. Hydrogen is regarded as the best gaseous candidate for natural gas due to its very fast burning velocity, and this combination is expected to improve lean-burn characteristics and decrease engine emissions [36]. The hydrogen blends in CNG can range from 5 to 30% by volume. Hythane is a 15% blend of hydrogen in CNG by energy content, which was patented by Frank Lynch of Hydrogen Components Inc, USA [37]. A typical 20% blend of hydrogen by volume in CNG is 3% by mass or 7% by energy. An overall comparison of the properties of hydrogen, CNG, and 5 % HCNG blend by energy and gasoline is given in Table 1. It is to be noted that the properties of HCNG lie in between those of hydrogen and CNG [4].

Properties	H ₂	CNG	HCNG	Gasoline
Stoichiometric volume fraction in air,(vol %)	29.53	9.43	22.8	1.76
Limits of flammability in air, (vol %)	4-75	5-15	5-35	1.0-7.6
Auto ignition temp. K	858	813	825	501-744
Flame temp in air K	2318	2148	2210	2470
Maximum energy for ignition in air, mJ	0.02	0.29	0.21	0.24
Burning velocity in NTP air, cm s ⁻¹	325	45	110	37-43
Quenching gap in NTP air, cm	0.064	0.203	0.152	0.2
Diffusivity in air cm ² s ⁻¹	0.63	0.2	0.31	0.08
Percentage of thermal energy radiated	17-25	23-33	20-28	30-42
Normalized flame emissivity	1.00	1.7	1.5	1.7
Equivalence ratio	0.1-7.1	0.7-4	0.5-5.4	0.7-3.8

Table 1. Overall comparison of properties of hydrogen, CNG, HCNG and gasoline[4].

Hydrogen also has a very low energy density per unit volume and as a result, the volumetric heating value of the HCNG mixture decreases (Table 2) as the proportion of hydrogen is increased in the mixture [38].

Properties	CNG	HCNG 10	HCNG 20	HCNG 30
H ₂ [vol %]	0	10	20	30
H ₂ [mass %]	0	1.21	2.69	4.52
H ₂ [energy %]	0	3.09	6.68	10.94
LHV [MJkg ⁻¹]	46.28	47.17	48.26	49.61
LHV [MJNm ⁻³]	37.16	34.50	31.85	29.20
LHV stoichiometric mixture [MJNm ⁻³]	3.376	3.368	3.359	3.349

Table 2. Properties of CNG and HCNG blends with different hydrogen content [39]

Many researchers have studied the effect of the addition of hydrogen to natural gas on performances and emissions in the past few years[40-65]. Blarigan and Keller investigated the port-injection engine fueled with natural gas–hydrogen mixtures [40]. Bauer and Forest conducted an experimental study on natural gas–hydrogen combustion in a CFR engine [41]. Wong and Karim analytically examined the effect of hydrogen enrichment and hydrogen addition on cyclic variations in homogeneously charged compression ignition engines. The results indicated that the addition of hydrogen can reduce cyclic variations while extending the operating region of the engine [42]. Karim et al. theoretically studied the addition of hydrogen on methane combustion characteristics at different spark timings. The theoretical results showed that the addition of hydrogen to natural gas could decrease the ignition delay and combustion duration at the same equivalence ratio. It indicated that the addition of hydrogen could increase the flame propagation speed, thus stabilizing the combustion process, especially the lean combustion process [43]. Ilbas et al. [44] experimentally studied the laminar burning velocities of hydrogen–air and hydrogen–methane–air mixtures. They concluded that increasing the hydrogen percentage in the hydrogen–methane mixture brought about an increase in the resultant burning velocity and caused a widening of the flammability limit (Figure 6).

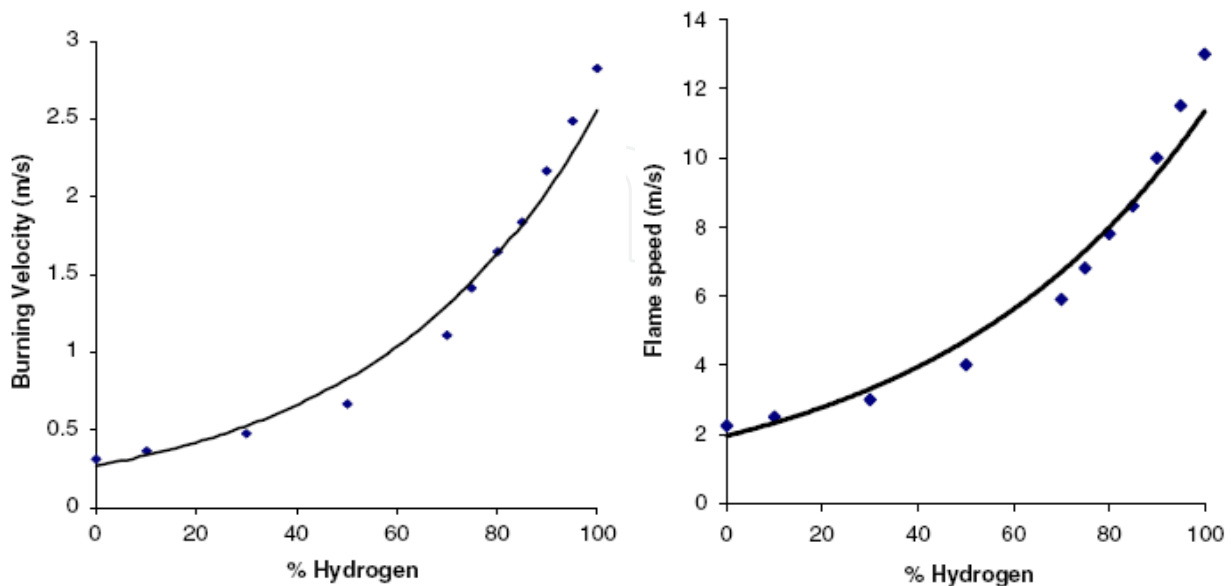


Figure 6. Burning velocities and flame speed for different percentages of hydrogen in methane ($\phi = 1.0$)[44].

Shudo et al., analyzed the characteristics combustion and emission of a methane direct injection stratified charge engine premixed with hydrogen lean mixture [45]. Their results showed that the combustion system achieved higher thermal efficiency due to higher flame propagation velocity and lower exhaust emissions. An increase in the amount of premixed hydrogen stabilizes the combustion process to reduce HC and CO exhaust emission, and increases the degree of constant volume combustion and NO_x exhaust emission. The increase in NO_x emission can be maintained at a lower level with retarded ignition timing without reducing the improved thermal efficiency. Nagalingam et al. [46] investigated hydrogen enriched CNG (hythane). He noted that the power was reduced due to the lower volumetric heating value of hydrogen compared with methane. However, since the flame speed of hydrogen was significantly higher than that of CNG, less spark advance was required to produce maximum brake torque (MBT). Wallace and Cattelan experimentally studied natural gas and hydrogen mixtures in a combustion engine. The experiments were conducted by studying the emissions of an engine fueled with a mixture of natural gas and approximately 15% hydrogen by volume [47].

Raman et al. [48] carried out an experimental study on SI engines fueled with HCNG blends from 0% to 30% of H₂ in a V8 engine. The authors observed a reduction in NO_x emissions using 15%-20% hydrogen blends with some increase in HC emissions as a result of ultra-lean combustion. The experiments were performed using a Chevrolet Lumina, which has six cylinders, four stroke cycles, is water cooled, with a total engine cylinder volume of 3.135 l, bore of 89 mm, stroke of 84 mm and compression ratio of 8.8:1. In their study, the BSFC of an 85/15 CNG/H₂ mixture was less than that of natural gas. The BSFC values decreased for both natural gas and the 85/15 CNG/H₂ mixture while spark timing (BTDC) values increased. The BSHC of CNG was higher than that of the fuel mixture. However, the BSNO_x emission values of the 85/15 CNG/H₂ mixture were higher than that of CNG. If a catalytic converter is used, the BSNO_x values are decreased drastically. Larsen and Wallace [49] conducted experimental tests on heavy-duty engines fueled by HCNG blends. The authors found that HCNG blends improve efficiency and reduce CO, CO₂ and HC emissions. Collier et al. examined the untreated exhaust emissions of a hydrogen-enriched compressed natural gas (HCNG) production engine [50]. They used variable composition hydrogen/NG mixtures and drew the following conclusions: the addition of hydrogen increases NO_x emission for a given equivalence ratio while it decreases total HC emissions which is in good agreement with Akansu's results [51]. They also found that as the hydrogen percentage increases, the lean limit of combustion is significantly extended. Hoekstra et al. [52] observed a reduction in NO_x for hydrogen percentages up to 30%, beyond this limit no improvement was observed. An important point was the higher flame speed and a consequent reduction of the spark advance angle to obtain the maximum brake torque, as already indicated by Nagalingam et al. [46]. Wang et al. investigated the combustion behavior of a direct injection engine operating on various fractions of NG–hydrogen blends [53]. The results showed that the brake effective thermal efficiency increased with the increase of hydrogen fraction at low and medium engine loads. The rapid combustion duration decreased, and the heat release rate and exhaust NO_x increased with the increase of hydrogen fraction in the blends. Their study suggested that the optimum hydrogen

volumetric fraction in NG–hydrogen blends is around 20% to achieve a compromise in both engine performance and emissions.

Ceper [54] studied different CH₄/H₂ mixtures experimentally and numerically. Her experimental study was performed with a four-stroke, four-cylinder, water cooled, Ford 1.8-liter internal combustion engine. CH₄/H₂ (100/0, 90/10, 80/20, 70/30) gas fuel mixtures of fuels were tested at different engine speeds and excess air ratios. Kahraman et al. [55] experimentally researched the performance and exhaust emissions of a spark-ignition engine fueled with methane-hydrogen mixtures (100% CH₄, 10% H₂ + 90% CH₄, 20% H₂ + 80% CH₄, and 30% H₂ + 70% CH₄) at different engine speeds and different excessive air ratios. The results demonstrated that while the speed and excess air ratio increased, CO emission values decreased. Furthermore increasing the excess air ratio also decreased the maximum peak cylinder pressure. Çeper et al. [56] experimentally analyzed the performance and the pollutant emissions of a four-stroke spark-ignition engine operating on natural gas-hydrogen blends of 0%, 10%, 20% and 30% at full load and 65% load for different excess air ratios. The results showed that while the excess air ratio increased, CO and CO₂ emission values decreased. In addition, increasing the excess air ratio led to a decrease in peak pressure values and by increasing the H₂ amount, peak pressure values were close to TDC, and the brake thermal efficiency values increased.

Sierens and Rossel [57] determined that the optimal HCNG composition to obtain low HC and NO_x emissions should be varied with engine load. Huang et al. [58] conducted an experimental study for a direct-injection spark-ignition engine fueled with HCNG blends under various ignition timings and lean mixture conditions. The ignition timing is an important parameter for improving engine performance and combustion. Dimopoulos et al. [59] optimized a state of the art passenger car natural gas engine for hydrogen–natural gas mixtures and high exhaust gas recirculation (EGR) rates in the major part of the engine map. Increasing the hydrogen content of the fuel accelerated combustion leading to efficiency improvements. Well-to-wheel analysis revealed paths for the production of the fuel blends still having overall energy requirements slightly higher than a diesel benchmark vehicle but reducing overall green house gas emissions by 7%.

Based on the results of an experimental test campaign carried out in ENEA labs, Ortenzi et al [60], aimed at identifying the potential of using blends of natural gas and hydrogen (HCNG) in existing ICE vehicles. The tested vehicle was an IVECO Daily CNG, originally fueled with natural gas and the tests were made on an ECE15 driving cycle to compare the emission levels of the original configuration (CNG) with the results obtained with different blends (percentage of hydrogen in the fuel) and control strategies (stoichiometric or lean burn). Dulger investigated an 80% CNG and 20% H₂ mixture burning SI engine numerically [61]. Swain et al. [62] and Yusuf [63] investigated the same mixture with a different engine. Yusuf used a Toyota 2TC type engine with the following specifications: year 1976 1:6 l, 1588 cc, maximum HP 88 and maximum speed of 6000 rpm, bore 85 mm, stroke 70 mm, compression ratio of 9.0:1 and four cylinder engine. The engine was tested at 1,000 rpm,

using best efficiency spark advance and light loading conditions. When the methane–hydrogen mixture was compared to pure methane operation with the same equivalence ratios, the methane and hydrogen mixture increased BTE and NO_x emissions while decreasing the best efficiency spark advantage, unburned HCs and CO. Moreover, the lean limit combustion of natural gas was reduced from 0.61 to 0.54. The lean limit of combustion was defined as an operation with at least 38% of the cycles not completing combustion. By hydrogen addition, the equivalence ratios could be reduced by about 15% without increasing combustion duration and ignition delay.

Ma and Wang [64], experimentally investigated the extension of the lean operation limit through hydrogen addition in an SI engine which was conducted on a six-cylinder throttle body injection natural gas engine. Four levels of hydrogen enhancement were used for comparison purposes: 0%, 10%, 30% and 50% by volume. Their results showed that the engine's lean operation limit could be extended through adding hydrogen and increasing load level (intake manifold pressure). The effect of engine speed on lean operation limit is smaller. At a low load level an increase in engine speed is beneficial in extending the lean operation limit but this is not true at high load level. The effects of engine speed are even weaker when the engine is switched to hydrogen enriched fuel. Spark timing also influences the lean operation limit and both over-retarded and over-advanced spark timing are not advisable. Road tests on urban transport buses were performed by Genovese et al. [65], comparing energy consumption and exhaust emissions for NG and HCNG blends with hydrogen content between 5% and 25% in volume. The authors found that average engine efficiency over the driving cycle increases with hydrogen content and NO_x emissions were higher for blends with 20% and 25% of hydrogen, despite the lean relative air fuel ratios and delayed ignition timings adopted. Having reviewed the main experimental papers published in the past, we conclude that numerical analysis also plays a fundamental role in research activities, allowing a better design of the experimental tests in terms of cost savings and time reduction[66-70].

4.1. Emissions

Air pollution is fast becoming a serious global problem arising from an increasing population and its subsequent demands. This has resulted in increased usage of hydrogen as fuel for internal combustion engines. Hydrogen resources are vast and it is considered as one of the most promising fuels for the automotive sector. As the required hydrogen infrastructure and refueling stations do not currently meet demand, the widespread introduction of hydrogen vehicles is not feasible in the near future. One of the solutions for this hurdle is to blend hydrogen with methane. Such types of blends take benefit of the unique combustion properties of hydrogen and at the same time reduce the demand for pure hydrogen. Enriching natural gas with hydrogen could be a potential alternative to common hydrocarbon fuels for internal combustion engine applications [71].

When experimental or simulation studies on reciprocating engines are carried out, much attention is paid to pollutant CO, HC and NO_x emissions. Nevertheless, although CO₂ is one

of the most important greenhouse gases, these emissions are not usually taken into account, and measurements and calculations of CO₂ emissions are omitted from many studies [72].

Fuel costs and their relationship to equivalent CO₂ emissions are represented in Figure 7 for several types of fuel ([73] and data from the authors). As observed, the global CO₂ emissions associated with CNG and their costs are lower than those produced by gasoline or diesel. Hydrogen produces lower CO₂ emissions than CNG, gasoline or diesel, but hydrogen always originates from renewable sources. Due to the high price of crude oil, in some cases the cost of H₂ is lower than that of gasoline or diesel. In any case, these data have been prepared without taking into account the possible effects of an increase in demand or mass production [72].

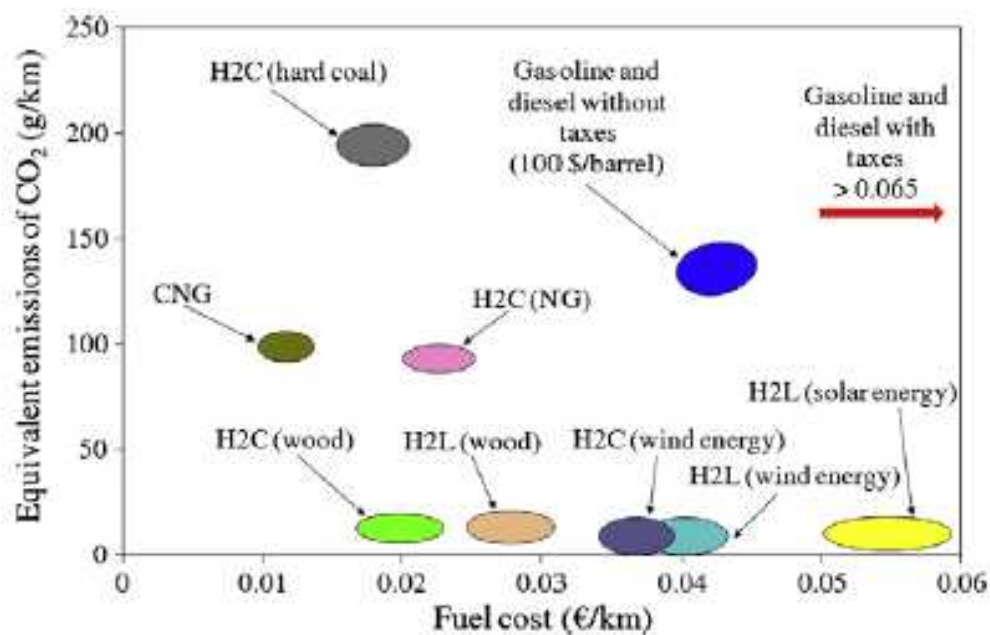


Figure 7. Cost and CO₂ emissions for several fuels [72].

All these performance parameters have a direct relationship with the exhaust emissions produced, often with contradictory effects. For instance, while higher compression ratios are favored in order to increase thermal efficiency, they also result in higher NO_x emissions because of the resultant higher combustion chamber temperatures. This is also the case when running stoichiometric fuel-air mixtures, as seen in Figure 8 (which is applicable to gasoline engines, but the general trends are similar for natural gas engines as well). In addition, while the combustion of lean fuel-air mixtures ($\phi < 1$) results in low NO_x emissions (as seen from Fig. 7) this can also result in lower power output. However, running an engine on fuel-rich mixtures ($\phi > 1$) is also undesirable and this results in high unburnt HC and CO emissions. Knock limits are also a factor when deciding ideal operating parameters. For instance if an engine is running too high a compression ratio, resistance to knock is lowered. This would require the need for spark retardation with respect to combustion TDC (which can affect thermal efficiency and therefore power output as well as exhaust emissions)[74].

Figure 9 illustrates the $BSNO_x$ (g/kWh) values versus equivalence ratios from different studies [75]. As seen in this figure, according to studies, with increasing H_2 percentage, $BSNO_x$ values increase or decrease. According to refs [62,49,57] and Bauer and Forest [41] (there is no data value in graphics), with increasing H_2 percentage, the $BSNO_x$ values increase. However, in the experiments performed by Raman et al. [48], with increasing H_2 percentage, the $BSNO_x$ values decrease. Moreover, if the equivalence ratios decrease, the $BSNO_x$ values reach a low value. It is interesting to note that Hoekstra et al. [52], as well as Larsen and Wallace [49], obtained extremely low NO_x emission.

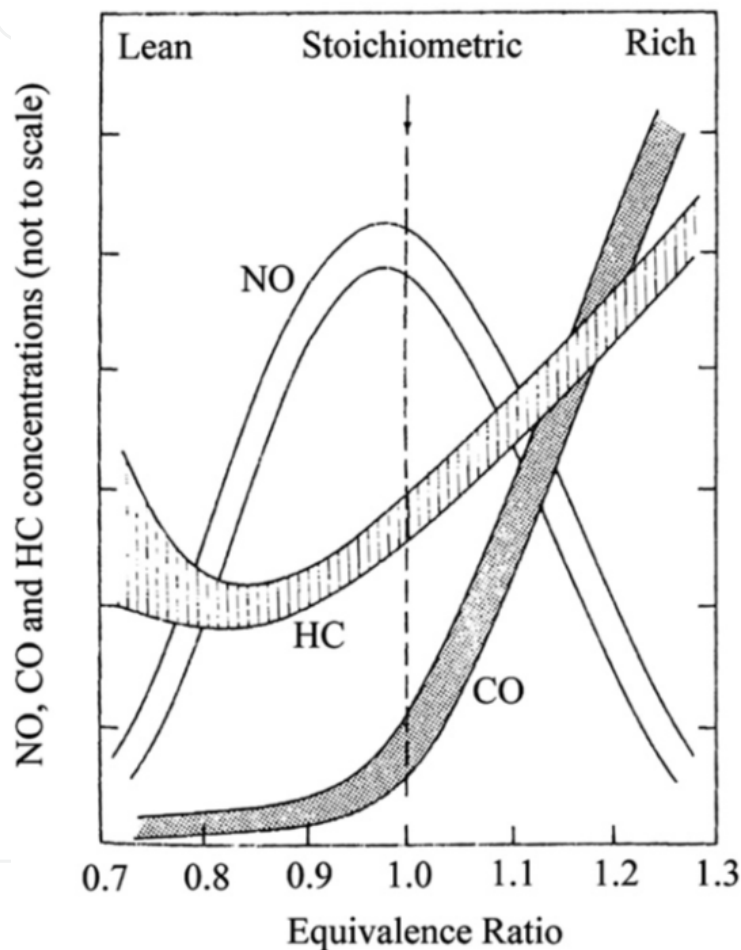


Figure 8. Typical NO, HC and CO trends with equivalence ratio in an SI engine, adapted from [74].

Figure 10 shows the $BSHC$ (g/kW h) values in different studies [75]. As seen in this figure, with increasing H_2 percentage and equivalence ratio, the $BSHC$ values decrease. If fuel is to be 100% H_2 fuel, the $BSHC$ value will be zero. We can say that $BSHC$ values decrease as the amount of H_2 increases. By increasing the equivalence ratios Swain et al. [62] obtained the highest $BSHC$ values in these studies. The maximum value is about 64 g/kW h, for a 20% H_2 and 80% CH_4 mixture with $\phi = 0.60$. However, hydrocarbon emissions of 20% H_2 and 80% CH_4 mixture are less than those of pure methane [62]. In this figure, the $BSHC$ values of Ref. [49] are at their highest value. $BSHC$ values increase with increasing engine load.

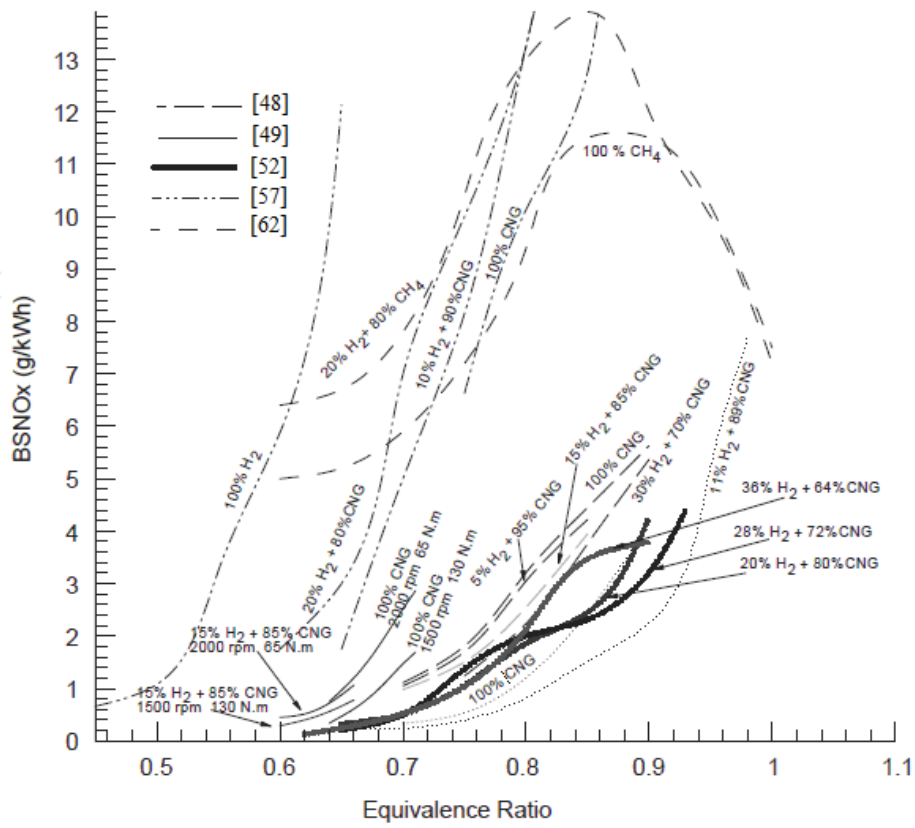


Figure 9. BSNO_x (g/kWh) values of different studies versus equivalence ratios[75].

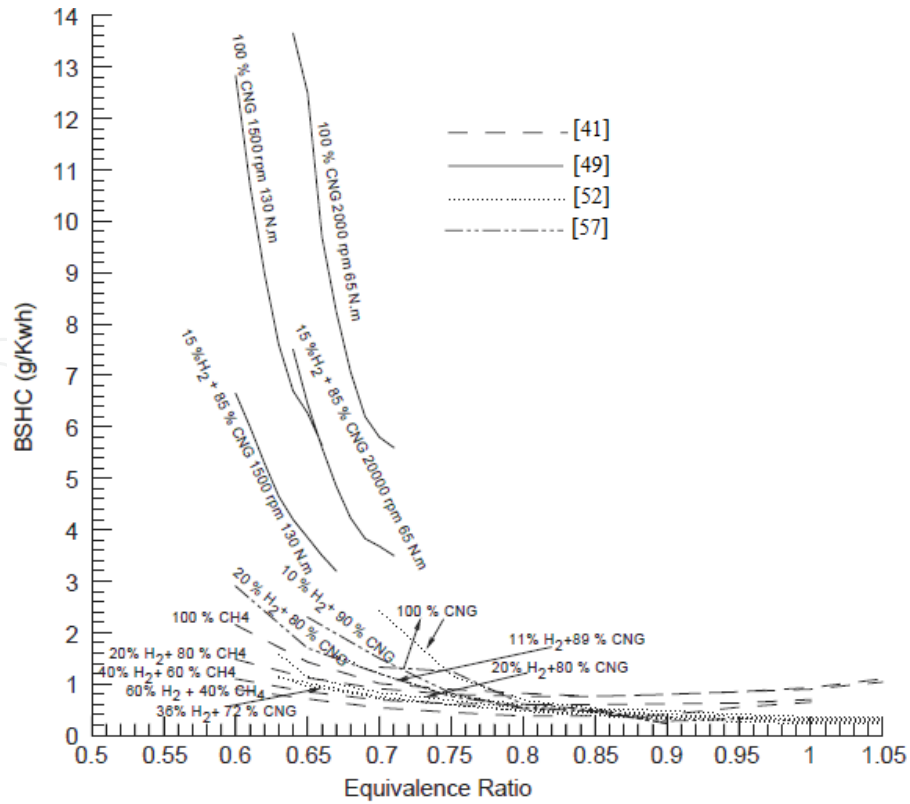


Figure 10. Brake specific hydrocarbons (BSHC g/kw h) values in different studies[75].

Larsen and Wallace obtained 1.65 and 2:41 g/kW h CO values at 1500 rpm, and $\phi = 0.65$ equivalence ratio, using an 85/15 CNG/H₂ and 100% CNG, respectively [49]. Yusuf measured all engine/fuel configurations performed similarly over normal operating ranges. An important variation occurred with rich mixtures. In addition, the 80/20 CH₄/H₂ mixture showed a small but significant reduction in BSCO output [62,63]. Bauer and Forest's experiments demonstrated that production of CO was highly dependent on combustion stoichiometry and less so on the engine. They obtained a general reduction in BSCO with the addition of hydrogen because of the reduction of carbon in the fuel. They added up to 60% hydrogen by volume and found that BSCO decreased up to 20 g/kW h (60/40 CH₄/H₂) at $\phi=1.0$. In the ultra lean region ($\phi<0.4$), an increase in BSCO was noted, due to incomplete combustion combined with sharply dropping power [41]. Figure 11 shows the BSCO emission values of some studies[75]. As seen in this figure, a ϕ value between 0.65 and 0.8 placed BSCO values at a dramatically low level.

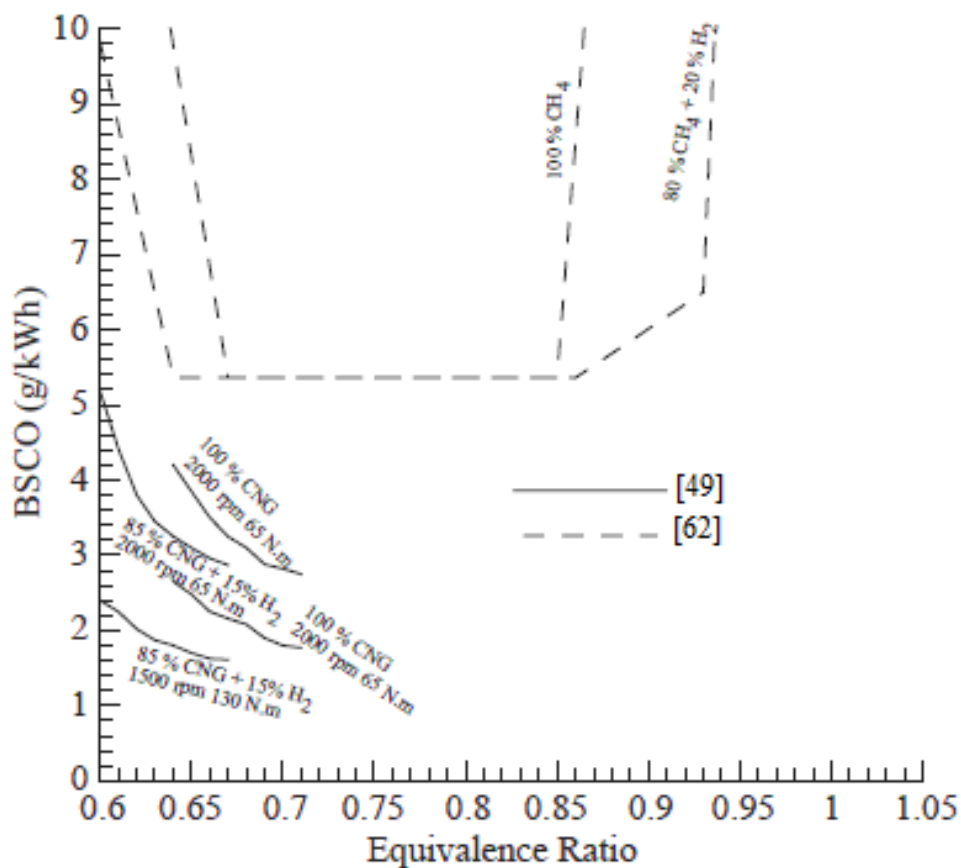


Figure 11. BSCO (g/kw h) values versus equivalence ratio in different studies[75].

Figure 12 gives the brake NO_x, HC, CO and CO₂ emission versus hydrogen fraction at various injection timings[76]. Brake NO_x emission increases with increasing hydrogen fraction when the hydrogen fraction is less than 10%, and it decreases with the increase of hydrogen fraction when the hydrogen fraction is larger than 10% at various injection timings. The comprehensive effects of in-cylinder temperature, excess air ratio and combustion duration contribute to this. As excess air ratio in this experiment is larger than

1.0 and combustion duration is slightly decreased with increasing hydrogen fraction, the effect of cylinder gas temperature plays an important part, thus the trend of brake NO_x emission is consistent with that of the maximum mean gas temperature. Brake HC emission decreases with the increase of hydrogen fraction. This is because the quench distance of the fuel blends is decreased and the lean flammability limit of the natural gas-hydrogen fuel blends is extended with hydrogen addition. Meanwhile, combustion is improved with the increase of hydrogen fraction, and this enhances the post-flame oxidation of the already formed HC. Furthermore, the C/H ratio decreases with increasing hydrogen fraction and this also contributes to the decrease of brake HC emission with the increase of hydrogen fraction.

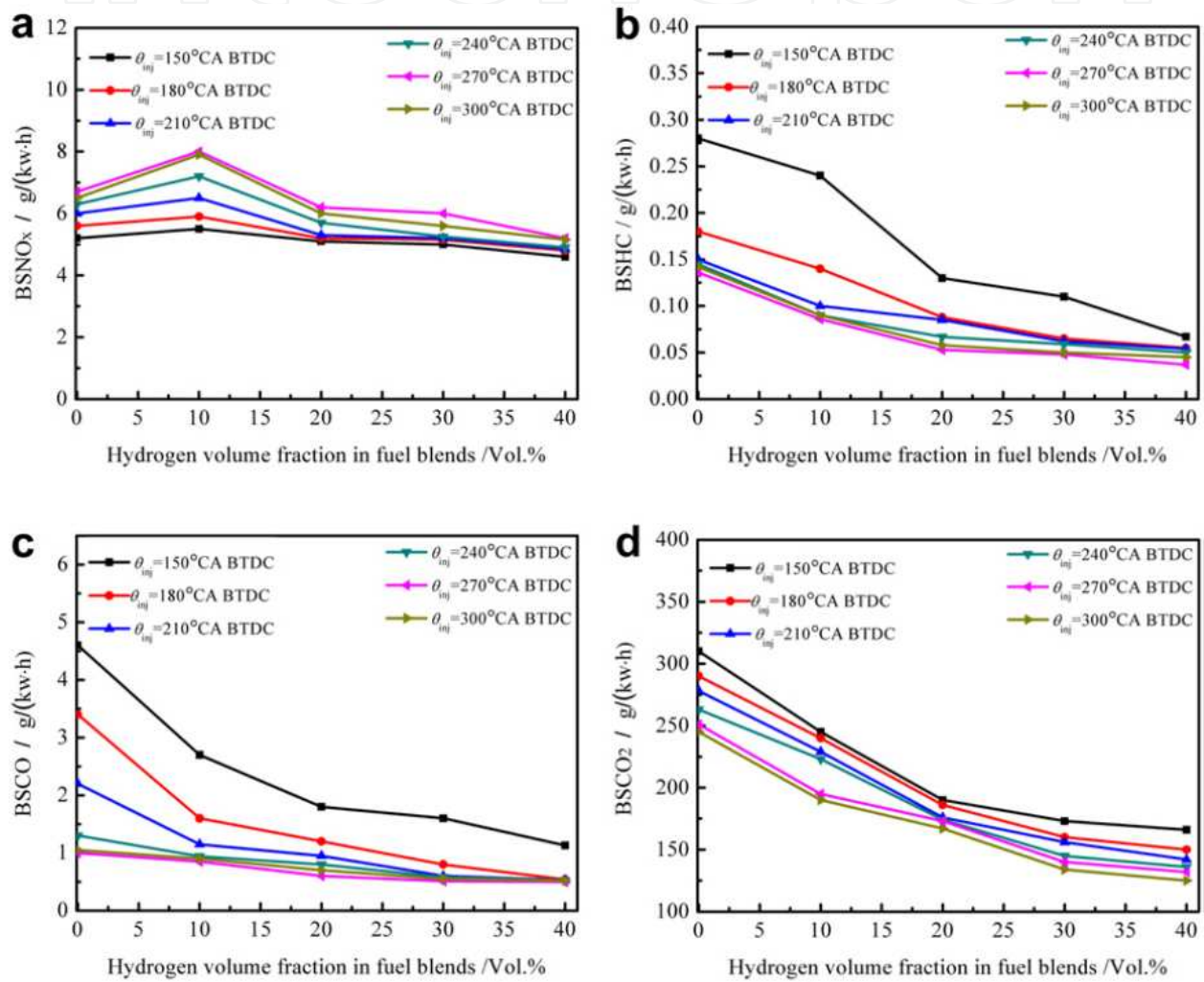


Figure 12. Brake NO_x , HC, CO and CO_2 emission versus hydrogen fractions. (a) Brake NO_x emission versus hydrogen fractions. (b) Brake HC emission versus hydrogen fractions. (c) Brake CO emission versus hydrogen fractions. (d) Brake CO_2 emission versus hydrogen fractions[76]

Brake CO emission decreases with increasing hydrogen fraction. As overall excess air ratio in the cylinder increases with hydrogen addition, and CO is strongly related to the air-fuel ratio, the sufficiency of oxygen in the cylinder makes the CO emission low. Also, combustion is improved with the increase of hydrogen fraction, and this enhances the post-flame oxidation of the already formed CO. Furthermore, the C/H ratio decreases with

increasing hydrogen fraction in the fuel blends and this also contributes to the decrease of brake CO emission with the increase of hydrogen fraction. Brake CO emission achieves its minimum value at a fuel-injection timing of 270 °CA BTDC. Brake CO₂ emission decreases with the increase of hydrogen fraction. The decrease in the C/H ratio of the mixtures with the increase of hydrogen fraction is responsible for this. A low carbon fraction produces low CO₂ concentration [76].

4.2. Cylinder pressure

Figure 13 shows the cylinder pressure at engine speeds of 2000 and 3000 rpm for different values of H₂ percentages (0, 3%, 5% and 8% in ref 77; 0, 10%, 20% and 30% in ref 54) and $\lambda=1.0$. For all cases, the cylinder pressure increased with the increase in the amount of H₂. The maximum pressures for the 8% H₂, 5% H₂, 3% H₂ and pure CNG occurred at 11, 12, 12.5, and a 13.5° crank angle ATDC respectively [77]. The maximum pressures for the 30% H₂, 20% H₂, 10% H₂ and pure CNG occurred at about 53, 48, 44, and a 36° crank angle ATDC respectively [54]. At an engine speed of 3000 rpm, the maximum cylinder pressures occurred at a 13.5° crank angle ATDC with their magnitudes being the highest of all values of H₂ percentage [77]. In Ref [54], the maximum cylinder pressure occurred at a 30° crank angle ATDC. In Ref [77], the compression ratio of the engine was 14:1 and in ref [54] the compression ratio of the engine was 10:1. So the maximum cylinder pressure values were obtained at 8% H₂ in both figures. For all the previous cases, the cylinder pressure increased with the increase in the amount of H₂. The explanation for this phenomenon is mainly due to fact that the flame speed of hydrogen is faster than the flame speed of CNG. Therefore, burning CNG in the presence of a small amount of hydrogen will result in faster and more complete combustion. This will result in higher peak pressure closer to TDC and it will produce a higher effective pressure [77].

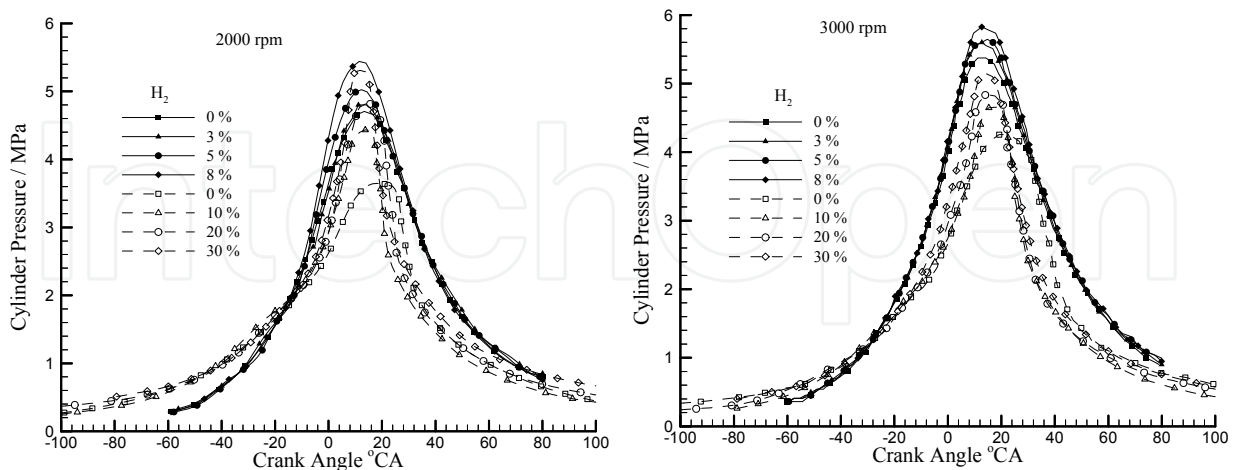


Figure 13. Cylinder pressure values versus the crank angle for different engine speeds and different H₂ fractions (solid ref [77] and dashed ref [54])

Figure 14 shows the in-cylinder pressure curve under various λ for different fuels: pure CNG, 30% HCNG, 55% HCNG [78]. From Figure 14(a), as the mixture is leaner, the

maximum in-cylinder pressure is smaller. Figure 14(b,c,d) shows further that the position of the maximum in-cylinder pressure is later before $\lambda=1.5$. On the other hand, when $\lambda > 1.5$, the maximum in-cylinder pressure is nearer the TDC.

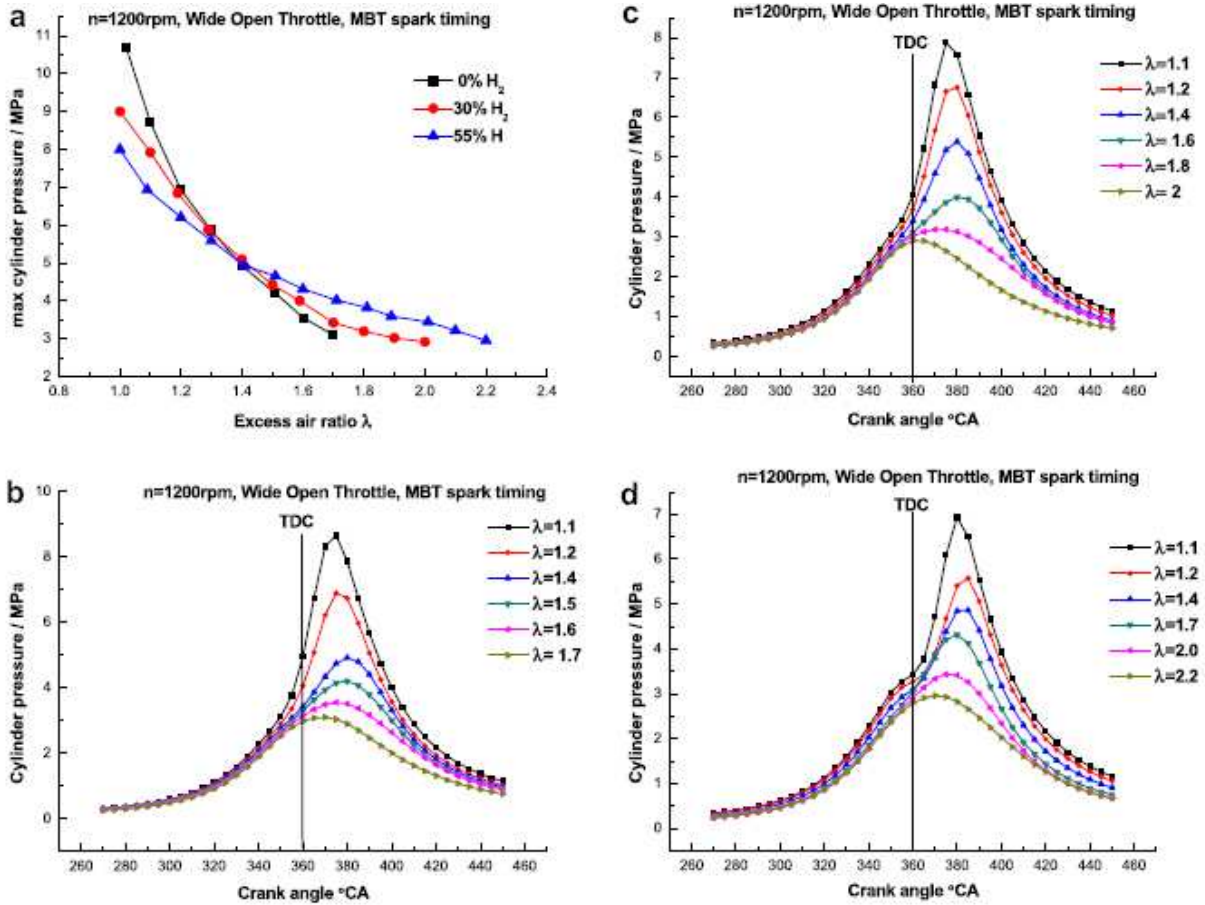


Figure 14. (a) Max cylinder pressure versus excess air ratio. (b) In-cylinder pressure for CNG. (c) In-cylinder pressure for 30% hydrogen volumetric ratio. (d) In-cylinder pressure for 55% hydrogen volumetric ratio[78].

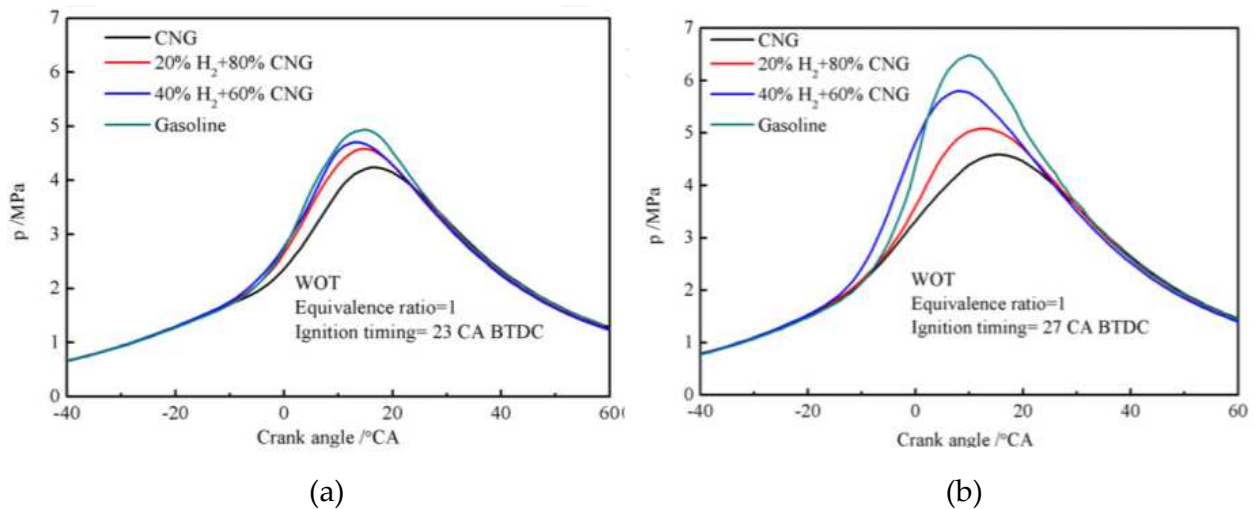


Figure 15. Cylinder pressure versus crank angle for 2000 and 3000 rpm in different fuels[79].

Figure 15 shows cylinder pressure versus crank angle for 2000(a) and 3000(b) rpm respectively [79]. As shown in these figures, the timing of the maximum cylinder pressure fueled with natural gas is postponed compared with that fueled with gasoline, and it advances as hydrogen is added.

4.3. Brake thermal efficiency

Figure 16 depicts BTE versus equivalence ratio [75]. As seen in this figure, the BTE of a 20% H₂ + 80% CH₄ mixture is higher than that of 100% CH₄ [57,62]. Since only one cylinder was used in the experiment it is expected that efficiency be lower compared to an experiment using a four-cylinder engine. According to the experiments in Ref[41], the BTE values decreased, while the H₂ percentage increased. The highest efficiency values were between 0.7 and 0.9 equivalence ratios. According to the study in Ref. [55], the maximum efficiency was at about $\phi=0.75-0.8$ for a 30% H₂+70% CH₄ mixture.. Also, effective efficiency had about a $\phi=0.75-0.8$ equivalence ratio [41,57,62].

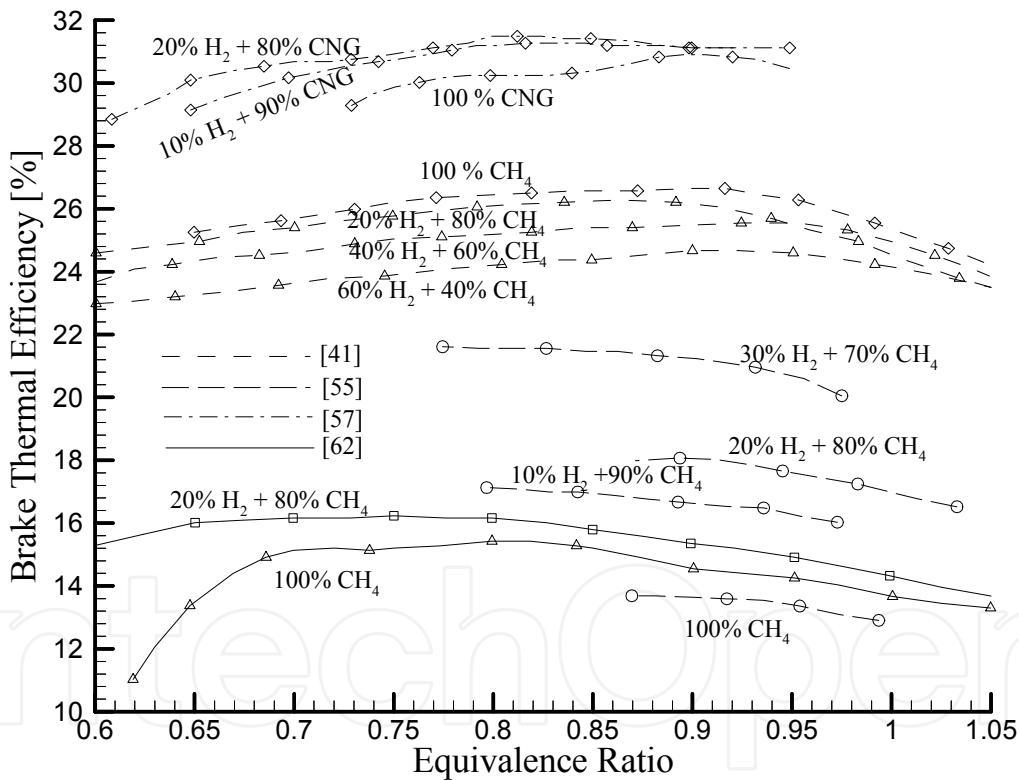


Figure 16. Brake thermal efficiency versus equivalence ratio

5. Conclusions and perspectives for further development

The results in this study can be summarized as follows:

- The ultimate goal of hydrogen economy is to displace fossil fuels with clean burning hydrogen and CNG is the best route to ensure the early introduction of hydrogen fuel into the energy sector.

- The lean-burn capability and flame burning velocity of the natural gas engine was improved by blending it with fast burning velocity fuel such as hydrogen.
- HCNG engines are superior to CNG engines from a fuel economy, power, and torque point of view due to better combustion.
- The addition of hydrogen to natural gas increases BMEP compared with that of natural gas combustion. This is due to the increased burning velocity of the mixture by hydrogen addition which shortens combustion duration and increases the cylinder gas temperature.
- The HCNG engine improves power by 3 - 4 % and torque by about 2 - 3 % compared to the CNG engine. The HCNG engine operates on the leaner side than the CNG engine which reduces fuel consumption by about 4% compared to CNG engine.
- The HCNG fuel reduces CO emissions and NO_x emissions more than the neat CNG operation. Thus the blended HCNG fuel is more environmentally friendly.
- Engine operating parameters have to be carefully chosen by the designer, taking into account their effect on engine performance and emission.
- Any attempt to control emissions by operating the engine with leaner mixtures has to take into account the effect on other variables like power.
- Compression ratio and equivalence ratio have a significant effect on both the performance and emission characteristics of the engine and have to be carefully designed to achieve the best engine performance characteristics.
- Higher engine rotational speeds can be used in lean mixtures to increase the power output of an engine operating on hydrogen while maintaining high efficiency and pre-ignition free operation.
- The variation in spark timing with hydrogen is very effective in controlling the combustion process.
- Higher compression ratios can be applied satisfactorily to increase power output and efficiency, mainly because of the relatively fast burning characteristics of hydrogen-air mixtures.
- The addition of hydrogen to methane gives a good alternative fuel to hydrocarbon fuels as it gives good flame stability, wide flammable regions and relatively higher burning velocity.
- NO_x emission values generally increase with increasing hydrogen content. However, if a catalytic converter, an EGR system or lean-burn technique are used, NO_x emission values can be reduced to extremely low levels.
- HC, CO₂ and CO emission values decrease with increasing hydrogen percentage.
- The addition of H₂ (up to 20-30% vol.) to NG may constitute an effective short-term solution for the green-house gases problem and at the same time to introduce H₂ into the fuel market without requiring changes in current engine technology.
- In conjunction with new and advanced technologies, hydrogen-methane mixture gases can provide a large part of the rapidly growing need for clean and affordable energy services in the world.

Future research of the hydrogen enriched compressed natural gas fuel include continuous improvement on performance and emissions, especially to reduce the hydrocarbon

emissions (including methane if necessary) which are currently not heavily regulated but will probably be more closely regulated in the future. Although the exhaust emissions from hydrogen-enriched natural gas are already very low, further refinement must be done in order to further reduce emissions and to achieve Enhanced Environmentally Friendly Vehicle (EEV) standards. Therefore finding the optimal combination of hydrogen fraction, ignition timing and excess air ratio along with other parameters that can be optimized is certainly a large hurdle. It is not only a challenge to locate the ideal combination of hydrogen fraction, ignition timing, and excess air ratio, but it can also be a large challenge to control these parameters. This requires sufficient control system to be developed for the HCNG engine to maximize the performance simultaneously minimizing the exhaust emissions. Other potential improvements include the reduction of emissions which can be transpire with the addition of a catalytic converter or by implementing an exhaust gas recycle system, lastly there is potential for performance improvements with an increase in the compression ratio[80].

As a result, today are faced with environmental problems, tomorrow hydrogen will solve all environmental problems due to road transports: Natural gas-hydrogen blends may be a potential bridge from today to tomorrow.

Abbreviations

AFR	Air-fuel ratio
ATDC	After top dead center
BSCO	Brake specific carbon monoxide
BSFC	Brake specific fuel consumption
BSHC	Brake specific hydrocarbon
BSNO _x	Brake specific nitrogen oxide
BTDC	Before top dead center
BTE	Brake thermal efficiency
CA	Crank angle (°)
CFR	Co-operative fuel research
CI	Compression ignition engine
CNG	Natural gas
CO	Carbon monoxide
CO ₂	Carbon dioxide
ECE15	European driving cycle
EGR	Exhaust gas recirculation
ENEA	Italian national agency for new technologies
HC	Hydrocarbon
HCNG	Hydrogen-natural gas blend
H ₂	Hydrogen
IC	Internal combustion engines
LNG	Liquid natural gas
LPG	Liquid petroleum gas

MBT	Maximum brake torque
NEDC	New European driving cycle
NG	Natural gas
NO _x	Nitrogen oxides
NTP	normal pressure and temperature
rpm	Revolutions per minute
SI	Spark-ignition engine
TDC	Top dead center
THC	Total unburned hydrocarbon
u _L	Laminar burning velocity
WOT	Wide open throttle

Greek symbols

ϕ	Equivalence ratio
λ	Excess air ratio

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